In cooperation with the Connecticut Department of Environmental Protection

The Thames Science Plan: Suggested Hydrologic Investigations to Support Nutrient-Related Water-Quality Improvements in the Thames River Basin, Connecticut

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By Elaine C. Todd Trench

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Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
$°F = (1.8 \times °C) + 32$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
$°C = (°F - 32) / 1.8$

Altitude, as used in this report, refers to distance above or below sea level. Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Concentration of chemical constituents is given in milligrams per liter (mg/L) or micrograms per liter (µg/L).

CTDEP, Connecticut Department of Environmental Protection
CWA, Clean Water Act
MADEP, Massachusetts Department of Environmental Protection
NPS, Nonpoint source
TMDL, Total maximum daily load
USEPA, U.S. Environmental Protection Agency
USGS, U.S. Geological Survey

The Thames Science Plan: Suggested Hydrologic Investigations to Support Nutrient-Related Water-Quality Improvements in the Thames River Basin, Connecticut

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Purpose, Development, and Organization of the Thames Science Plan

The Thames Science Plan is the result of a cooperative project between the U.S. Geological Survey (USGS) and the Connecticut Department of Environmental Protection (CTDEP). The Science Plan outlines water-quality investigations that could provide information necessary for the CTDEP to develop water-quality management and restoration strategies for nutrient-related problems in the Thames River Basin. The purpose of the Science Plan is to identify information that would support CTDEP in developing Total Maximum Daily Load analyses (TMDLs) for nutrients for individual water bodies and stream reaches in the Thames Basin, and eventually for the entire basin, as required under the Federal Clean Water Act.

Development of the Science Plan included a review of the historical database for the Thames River Basin, focusing primarily on water-quality monitoring and interpretive studies conducted by the USGS from 1970 to 2004. Selected additional water-quality information from CTDEP, other state and federal agencies, and academic and private sources has also been reviewed. A complete review and synthesis of all sources of nutrient-related water-quality information for the Thames River Basin is beyond the scope of this Science Plan.

Information on important nutrient-related issues and questions in the Thames River Basin has been obtained from many sources, including reports from the Thames River Water-Quality Symposium, sponsored by the CTDEP on April 30, 2002 (Connecticut Department of Environmental Protection, 2002c). The Thames Technical Workshop, sponsored by the USGS on April 23-25, 2003, provided additional insight into these issues and questions. The Technical Workshop included discussions at several field locations in the Thames Basin, presentations by USGS researchers on freshwater and estuarine nutrient topics, and a moderated discussion among participants from the CTDEP, the USGS, and the U.S. Environmental Protection Agency (USEPA).

The Thames Science Plan is organized into five major sections:

- The *Background* section provides information on the importance of nutrients in freshwater and marine environments, describes nutrient sources, briefly describes the environmental setting of the Thames River Basin, and summarizes water-quality management issues related to nutrients in the Thames Basin.
- The *Conceptual Model of the Thames River Basin* summarizes the current scientific understanding of nutrient dynamics in the freshwater and estuarine ecosystems of the Thames Basin, and incorporates information from a variety of sources in describing important aspects of these ecosystems.
- The *Review of the Historical Database for the Thames River Basin* summarizes the data resources available from the USGS, CTDEP, U.S. Army Corps of Engineers, and Massachusetts Department of Environmental Protection, with emphasis on information from the USGS; additional sources of information are noted.
- The *Assessment of Information Needs* summarizes key pieces of information that are currently unavailable for understanding and managing nutrient-related water-quality problems in the Thames Basin, including various kinds of monitoring data as well as process-oriented information. A series of flowcharts presents the information needs in diagrammatic form.
- The *Summary of Suggested Investigations to Fulfill Information Needs* provides brief descriptions for a series of investigations that would provide, collectively and sequentially, information needed by water-resource managers to understand and manage nutrient-related water-quality problems in the Thames Basin. Additional flowcharts relate the suggested investigations to the identified information needs.

Italics or ***bold italics*** have been used in this report to highlight key concepts, issues, and information needs.

Background

Management decisions of increasing complexity require information suitable for protection and restoration of water quality, aquatic life, and habitat in rivers, lakes, and estuaries. Water-quality problems resulting from excessive nutrients in freshwater and estuaries are among the most widespread and complex issues currently facing water managers.

The Importance of Nutrients

Carbon, hydrogen, nitrogen, and phosphorus are major constituents of the cellular protoplasm of organisms (Wetzel, 1983, p. 251). Nitrogen and phosphorus have important effects on the biological productivity of natural waters, and these nutrients are the primary focus of the Thames Science Plan. Organic carbon in an aquatic ecosystem has a complex and pivotal relationship with the productivity of living organisms (Wetzel, 1983, p. 140), and consequently an evaluation and understanding of this constituent is also necessary in any consideration of nutrient-related problems in the Thames River Basin.

Phosphorus and nitrogen are essential nutrients for plant growth. Free-floating aquatic plants such as algae depend on dissolved nitrogen and phosphorus compounds for nutrients (Hem, 1985, p. 128). Nitrogen availability rarely limits aquatic plant growth in freshwater, whereas phosphorus concentrations in natural or near-natural streams are generally low enough to limit plant growth. Excessive phosphorus concentrations promote the growth of aquatic algae and resulting eutrophic conditions in freshwater (Hem, 1985, p. 128), whereas research indicates that excessive nitrogen concentrations are more likely to promote algal growth and eutrophication in many estuarine environments and coastal ecosystems in the temperate zone (National Research Council, 2000, p. 66).

Excessive growth of algae, often called an algal bloom, can have numerous adverse effects on water quality and aquatic habitat. When the plants in a dense growth of algae die, they decompose, consuming oxygen in the water and contributing to a condition called hypoxia, or low dissolved oxygen. An algal bloom also can affect water quality and aquatic habitat by increasing turbidity, limiting light penetration, and altering the composition of the food chain. During the day, the photosynthetic activity of aquatic plants, including algae, consumes carbon dioxide and releases oxygen to the water, whereas during the night, as photosynthesis ceases, aquatic plants and animals continue to respire, consuming oxygen and producing carbon dioxide. Consequently, water bodies with large algal populations may experience large daily fluctuations in dissolved oxygen concentrations and pH, affecting habitat conditions for other aquatic organisms.

Sources of Nutrients in the Thames River Basin

Nitrogen and phosphorus constituents in streams are derived from natural sources and from many human uses of land and water resources. Major sources of nitrogen and phosphorus in Connecticut include decaying plants, animal wastes, fertilizers, and municipal and industrial wastewater. Historically, detergents have contributed substantial amounts of phosphorus to streams. Atmospheric deposition contributes nitrogen and minor amounts of phosphorus to the land surface. Ground-water inflow may contribute major or minor quantities of nutrients to streams, depending on land use effects and hydrogeologic conditions. Some forms of phosphorus are chemically reactive, adhering to particulate materials in water and consequently accumulating in stream sediment. Minerals in rocks and soil are not major sources of nitrogen or phosphorus in Connecticut streams.

Phosphorus concentrations in the Quinebaug River, and other streams in Connecticut, were historically very high during the mid-20th century as a result of untreated or minimally treated wastewater discharges and phosphorus in detergents. Sediments in streambeds and impoundments continue to constitute a reservoir of nutrients that may be recycled into the water column under some conditions.

Environmental Setting of the Thames River Basin

The Thames River Basin is a 1,478-square mile drainage area located primarily in eastern Connecticut, with upstream drainage areas in south-central Massachusetts and western Rhode Island (fig. 1). The major freshwater streams in the basin are the Shetucket and Quinebaug Rivers. The Quinebaug River is considered a tributary to the Shetucket River, although, at their confluence in Norwich, the drainage area and average discharge of the Quinebaug are greater than those of the Shetucket (Healy and others, 1994, p. 94). In discussing the freshwater resources of the Thames Basin, it is convenient to refer to the Shetucket and Quinebaug Rivers separately, with the Quinebaug River draining the eastern portion of the Thames Basin, and the Shetucket River (upstream from its confluence with the Quinebaug) draining the central and western portions of the basin. The tidal Thames River begins at the confluence of the Shetucket River and the much smaller Yantic River in Norwich. The Thames River flows about 16 miles from Norwich Harbor to Long Island Sound.

The Thames River Basin is largely forested, with 76 percent of the drainage basin covered by undeveloped forested areas and wetlands (fig. 2, table 1). In many parts of the watershed, forested areas are interspersed with agricultural areas, rural villages, mill villages, and small urban areas. Most urban areas have developed along major streams. Municipal wastewater-treatment facilities discharge treated wastewater to streams in both the Massachusetts and Connecticut portions of the watershed, and so there are interstate issues related to the quality of water flowing into Connecticut. Numerous impoundments are located along the major streams in both states, and consequently there are also water quality issues related to streamflow regulation. Historic sediments in streams and impoundments may serve as reservoirs of nutrients and other pollutants. Warm weather algal blooms and eutrophication are common problems in some impoundments and stream reaches, particularly in the Quinebaug River Basin. In the Thames estuary, where the cities of Norwich and New London and several industries have point discharges, low dissolved oxygen contributes to aquatic life impairment, and the interaction of tidal cycles with variable freshwater inflows creates a dynamic and complex environment.

Despite the significant water-quality problems in the Thames River Basin, the valleys of the Quinebaug and Shetucket Rivers have been termed “the Last Green Valley” in the highly urbanized region that extends from Boston to Washington D.C., and a substantial part of the drainage area has been designated a National Heritage Corridor (National Park Service, undated). Consequently, water-quality management efforts in the Thames Basin include protection of existing resources in relatively unimpaired areas as well as restoration in impaired areas.

Water-Quality Management Issues

Effective action to address nutrient-related water-quality problems in the Thames River Basin requires scientific information on the occurrence, sources, cycling, and transport of nitrogen, phosphorus, and organic carbon in the environment. Water-resource managers could use this information in designing programs to improve water quality.

Provisions of the Federal Clean Water Act (CWA), which is administered by the USEPA, require each state to monitor, assess, and report on the quality of its waters (Connecticut Department of Environmental Protection, 2004a, b). Specifically, states are required to:

1. Adopt water-quality standards,
2. Assess surface waters to evaluate compliance with these standards,
3. Identify waters not currently meeting the standards, and
4. Develop Total Maximum Daily Load (TMDL) analyses and other management plans to bring water bodies into compliance with the standards.

The USEPA has developed guidance to assist states in assessing nutrient impairment of water bodies and in developing regionally based numeric criteria for river and stream systems (U.S. Environmental Protection Agency, 2000). The criteria development process is currently (2004) in progress.

Surface-water assessments are reported biannually by each state as required under Section 305 (b) of the CWA. In Connecticut, this document is called the Water-Quality Report to Congress (Connecticut Department of Environmental Protection, 2004b). Water bodies that have been identified as not meeting designated uses are also reported biannually in a document called the List of Connecticut Water Bodies Not Meeting Water Quality Standards, as required under Section 303 (d) of the CWA. Several water bodies or stream reaches in the Thames River Basin are on the 303 (d) Lists for Massachusetts and Connecticut because of nutrient-related water-quality impairments (table 2) (Connecticut Department of Environmental Protection, 2004a; Kennedy and others, 2002).

Table 1. Land use in the Thames River Basin.

[Numbers may not total to 100 percent because of rounding and because miscellaneous land-use categories that total less than 1 percent of basin area have not been included in the table]

Basin name	Drainage area (in square miles)	Land use (in percent)				
		Water	Wetland	Forest	Agriculture	Urban
French River	112	5.9	10.0	60.3	8.7	14.3
Fivemile River	76.4	3.1	8.8	74.3	7.3	5.8
Moosup River	89.1	1.0	6.8	78.5	9.0	4.2
Pachaug River	63.0	4.2	8.0	73.1	9.6	4.4
Quinebaug Main Stem	398	2.3	9.4	65.4	14.2	7.9
Total Quinebaug at confluence with Shetucket River	739	2.9	9.0	67.8	11.6	7.9
Willimantic River	226	2.0	9.0	68.5	11.1	8.6
Natchaug River	176	2.1	8.4	73.2	10.4	5.3
Shetucket Main Stem	125	1.6	7.7	66.8	14.8	8.2
Total Shetucket without Quinebaug	526	2.0	8.5	69.7	11.8	7.4
Total Shetucket at confluence with Thames River	1,265	2.5	8.8	68.6	11.7	7.7
Yantic River	97.8	2.9	7.6	61.9	19.3	7.5
Thames Main Stem	108	5.4	6.6	62.2	3.3	21.7
Total Thames at mouth at Long Island Sound	1,471	2.8	8.5	67.7	11.6	8.7

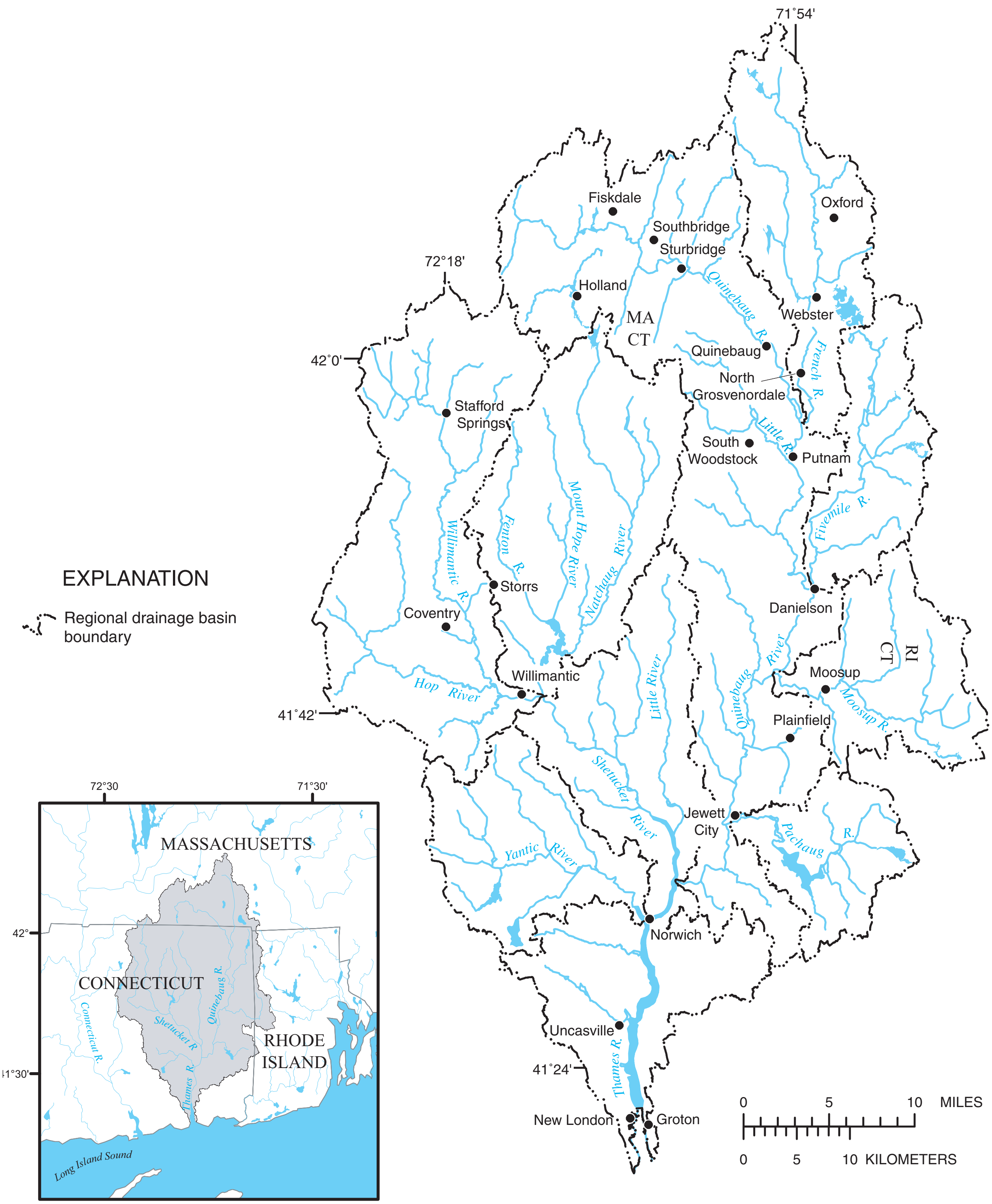

Figure 1. Map of Thames River Basin, showing major streams and subbasins.

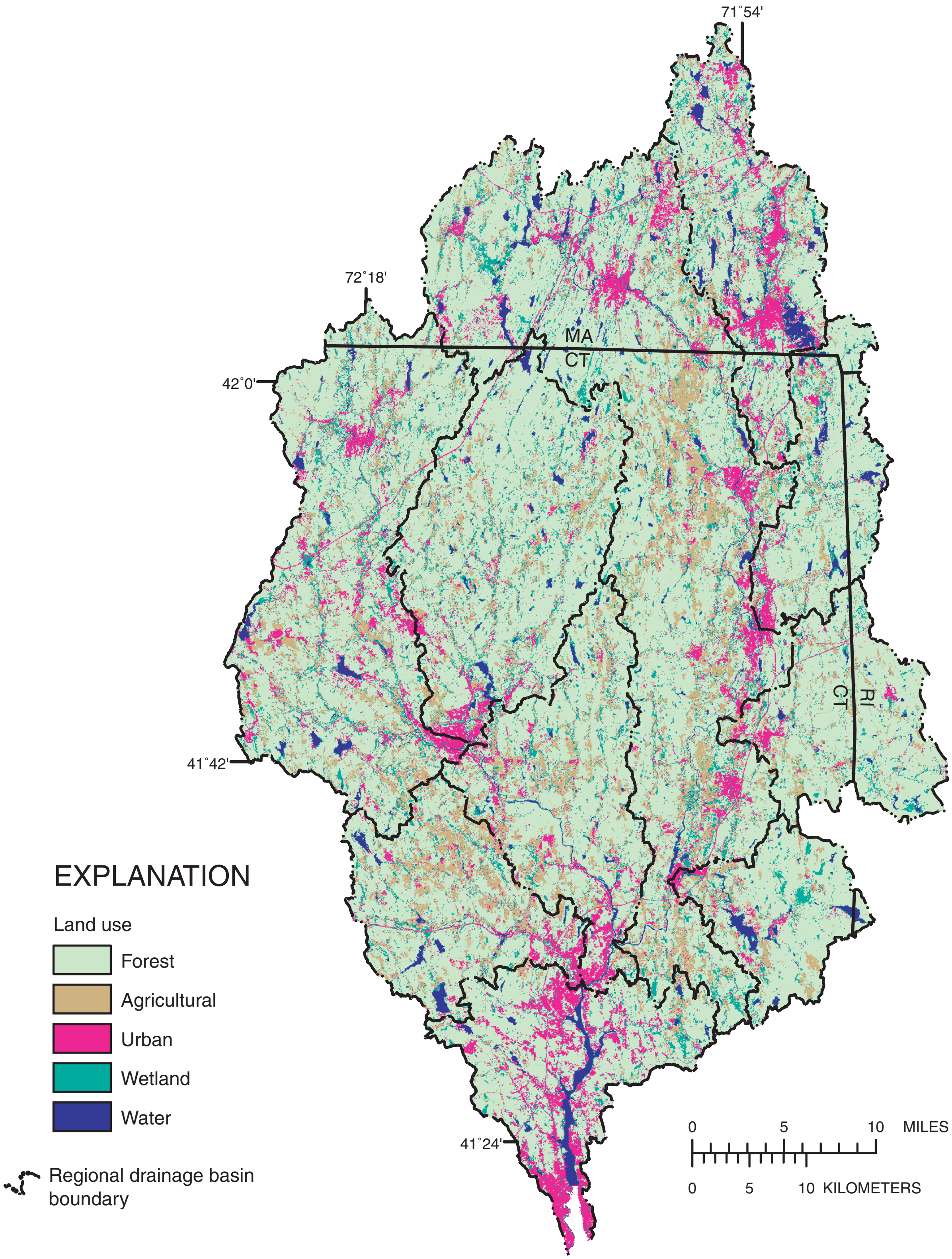

Figure 2. Map of the Thames River Basin, showing land uses and major subbasins. (Data from Vogelmann and others, 2001.)

Several impoundments and freshwater stream reaches in the Quinebaug River Basin are on the Connecticut 303 (d) list because of high nutrient levels and resulting eutrophication, and the Thames estuary is on the 303 (d) list because of a seasonal low dissolved oxygen problem. Excessive nutrients cause water-quality problems in many developed areas of the basin. The major nutrient sources are known, but the most important sources, processes, and causes have not been identified and quantified for all impaired locations.

The TMDL process (table 3), developed by the USEPA and implemented by states and other regulatory entities, provides a framework to restore impaired waters by establishing the maximum amount of a pollutant that a water body can assimilate from all sources (point, nonpoint, and natural) without adverse impact to aquatic life, recreation, or other public uses (Connecticut Department of Environmental Protection, 2004b, p. 2). The USEPA, in its Nonpoint Source Program and Grants Guidelines, also has promoted the development and implementation of Watershed-Based Plans to protect unimpaired waters and restore waters impaired by nonpoint source pollution (U.S. Environmental Protection Agency, 2003, p. 60658-59). Development of a Watershed-Based Plan, under Section 319 of the CWA, includes several management elements (table 4) and incorporates any TMDLs that have been developed for the watershed.

In April 2002, the CTDEP convened a Thames River Water-Quality Symposium to review the water-quality investigations, research, and modeling efforts that have been conducted in the Thames Basin by government agencies, academic researchers, and the private sector. The day-long symposium raised numerous questions and resulted in a set of recommendations (fig. 3) (Connecticut Department of Environmental Protection, 2002c). These recommendations constitute an important starting point for CTDEP as the agency determines how to manage water-quality restoration efforts in the Thames Basin.

Table 2. Water bodies in the Thames River Basin not meeting water-quality standards because of nutrient-related problems.

[Sources: Connecticut Department of Environmental Protection, 2004a, Appendix B; Kennedy and others, 2002, p. 16–18; Format differs for state documents for Connecticut and Massachusetts. Other impairments not specifically related to nutrients may be present but are not listed here. Locations for Connecticut water bodies are shown in figure 1. DO, dissolved oxygen; WWTF, wastewater-treatment facility]

Water body segment		Impaired designated use	Cause (or potential cause) of impairment
Name	Location		
	French River Basin		
Dutton Pond	Leicester, Mass.		Nutrients
Peter Pond	Dudley, Mass.		Nutrients, organic enrichment/low DO
Rochdale Pond	Leicester, Mass.		Nutrients, organic enrichment/low DO
Thayers Pond	Oxford, Mass.		Nutrients
French River	Webster-Dudley, Mass. WWTF to Connecticut state line		Nutrients, organic enrichment/low DO
French River	From mouth at Quinebaug River upstream to North Grosvenordale Pond, Thompson, Conn.	Aquatic life support	Cause unknown (algal growth, chlorophyll *a*, nutrients)
	Quinebaug River Basin		
Alum Pond	Sturbridge, Mass.		Organic enrichment/low DO
Glen Echo Lake	Charlton, Mass.		Organic enrichment/low DO
Quinebaug River	Southbridge WWTF, Southbridge, Mass. to West Dudley impoundment, Dudley, Mass.		Nutrients
West Thompson Lake	Impoundment of Quinebaug River in Thompson, Conn.	Aquatic life support; primary contact recreation	Organic enrichment, low DO, algal growth, chlorophyll *a*, nutrients
Quinebaug River	From confluence with Moosup River upstream to Putnam, Conn. WWTF	Aquatic life support	Cause unknown (algal growth, chlorophyll *a*, flow alteration, organic enrichment, low DO)
North Running Brook	From mouth at Muddy Brook upstream to input from ditch in farm field	Aquatic life support	Cause unknown (organic enrichment, low DO, nutrients)

Table 2. Water bodies in the Thames River Basin not meeting water-quality standards because of nutrient-related problems.—Continued

[Sources: Connecticut Department of Environmental Protection, 2004a, Appendix B; Kennedy and others, 2002, p. 16–18; Format differs for state documents for Connecticut and Massachusetts. Other impairments not specifically related to nutrients may be present but are not listed here. Locations for Connecticut water bodies are shown in figure 1. DO, dissolved oxygen; WWTF, wastewater-treatment facility]

Water body segment		Impaired designated use	Cause (or potential cause) of impairment
Name	Location		
Quinebaug River Basin—Continued			
Aspinook Pond	Impoundment of Quinebaug River in Canterbury, Griswold, and Lisbon, Conn.	Primary contact recreation	Algal growth, chlorophyll *a*, nutrients
Quinebaug River	From mouth at Shetucket River upstream to outlet of Aspinook Pond, Conn.	Aquatic life support	Cause unknown (algal growth, chlorophyll *a*, nutrients)
Shetucket River Basin			
Versailles Pond	Impoundment of Little River, southeast corner of Sprague, Conn.	Aquatic life support	Organic enrichment/low DO
Yantic River Basin			
Yantic Pond and tributary -- Norwich Landfill	From mouth at Yantic River upstream to upstream boundary of landfill influence	Aquatic life support	Organic enrichment/low DO/un-ionized ammonia
Kahn Brook	From mouth at Yantic River, Bozrah, upstream to chicken farm	Aquatic life support	Cause unknown (nitrate, phosphorus)
Thames River Estuary			
Thames River Estuary	Norwich Harbor downstream to Poquetanuck Cove, Poquetanuck Cove and Trading Cove	Aquatic life support	Nutrients, organic enrichment/low DO

Table 3. General components in Total Maximum Daily Load (TMDL) process implemented by state water-management agencies.

[Source: U.S. Environmental Protection Agency, 1999, fig. 1-2]

Components in TMDL development	
1.	Identify Problem
2.	Develop Numeric Targets
3.	Source Assessment
4.	Link Targets and Sources
5.	Load Allocation
6.	Develop Monitoring and Review Plan
7.	Develop Implementation Plan

Table 4. Management elements in Watershed-Based Plans implemented by state water-management agencies.

[Source: U.S. Environmental Protection Agency, 2003, p. 60659; NPS, nonpoint source]

Management elements in Watershed-Based Plans	
a.	Identify causes and sources to be controlled to achieve estimated load reductions
b.	Estimate load reductions expected for management measures
c.	Describe NPS management (measures to achieve load reductions
d.	Estimate technical and financial assistance needed
e.	Develop information/education component
f.	Develop schedule for implementing NPS management measures
g.	Describe interim measurable milestones for tracking implementation
h.	Develop criteria to assess load reduction achievement and progress toward water-quality standards attainment
i.	Develop monitoring component to evaluate effectiveness of implementation

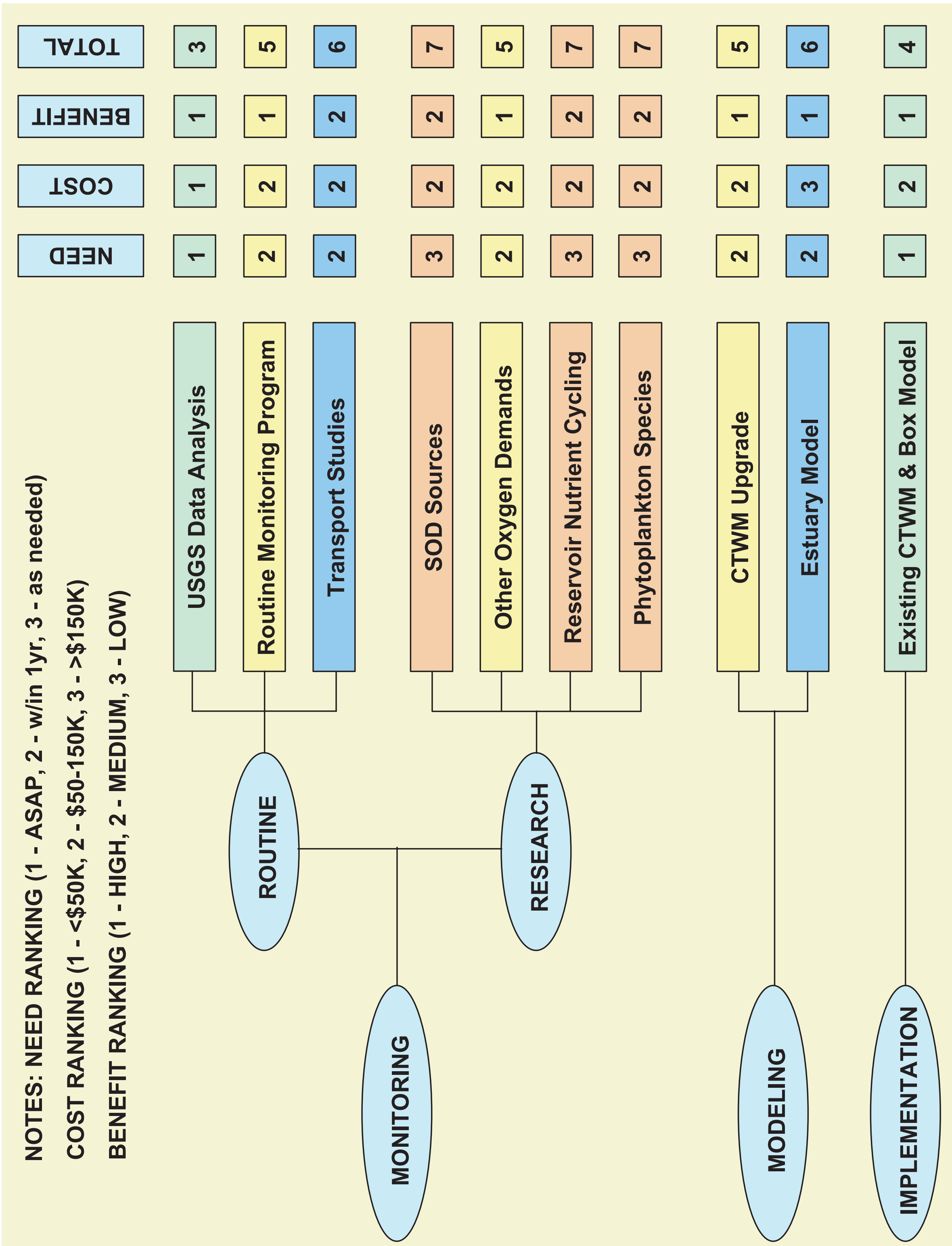

Figure 3. Ranking of information needs and suggested investigations from the Thames Symposium, April 2002 (Connecticut Department of Environmental Protection, 2002c).

Recommendations from the Thames Symposium have been reviewed as part of the information-gathering process for this project, and elements of these recommendations, as well as recommendations and observations from USGS researchers and others, have been incorporated into the Science Plan. The Science Plan builds on the work of the Thames Symposium by identifying specific projects and tasks necessary to address recommendations identified in the Symposium, by noting some of the data limitations that interfere with the accomplishment of some recommendations in the near term, and by outlining a sequence of investigations that could provide the information necessary to address these recommendations.

Scientific investigations could contribute to the TMDL process (table 3), the development of Watershed-Based Plans (table 4), and the more general goal of water-quality restoration in several ways. Suggested investigations could:

1. *Evaluate or interpret* existing information;
2. *Monitor and assess* water bodies;
3. *Develop new approaches* and tools for monitoring, analysis, interpretation, and modeling; and
4. *Share information and technology* (Shipp and Cordy, 2001).

The Thames Science Plan addresses purposes (1) and (4), and investigations suggested in the Science Plan have the potential to address all of these purposes.

CTDEP plans to follow an adaptive implementation strategy in the TMDL process, in which the agency works immediately on known problems while continuing to study areas where more information is needed (Connecticut Department of Environmental Protection, 2002c). This approach is analogous to a computer program that iteratively approaches a solution. With each iteration of the process, new and improved information refines the understanding of the system, and enables a closer approach to a true solution to the water-quality problems of the Thames River Basin.

Conceptual Model of the Thames River Basin

A key factor in understanding water quality in the Thames River Basin, or any drainage basin, is understanding how the many processes operating locally at a small scale interact to create the water-quality conditions and impairments identified at the watershed scale.

An over-arching concept from scientific research is that each watershed, ecosystem, river, or estuary is different. The same processes are taking place all the time, but the magnitude and rates of these processes vary in different locations, and consequently each river has a different story (F.J. Triska, U.S. Geological Survey, oral commun., 2003). Landscapes, including valley bottoms, are the products of processes, including fluxes of water, sediment, and organic material; interactions of these fluxes with the surrounding landscape, including plants and animals; and the history of these fluxes and interactions (J.E. O'Connor, U.S. Geological Survey, oral commun., 2003). The interactions among processes are surprisingly complex, and the processes operate within a hierarchy of spatial and temporal scales.

Complex problems confront CTDEP water managers as they attempt to develop a scientifically defensible nutrient TMDL for the Thames River Basin. These problems have been articulated on a conceptual level by Puckett and Triska (1996, p. 2-3); their discussion of the scientific understanding of nitrogen cycling applies to other constituents as well:

> Our lack of understanding of the linkages among the various controlling processes as we proceed from small-scale study areas to successively larger watersheds is one of the most poorly developed aspects of nitrogen-cycling theory (and most other water quality issues). This seemingly basic issue limits our ability to apply what we learn in small, relatively homogeneous research settings to the larger and more complex settings representing scales that affect human communities. Although there are numerous limitations due to gaps in our knowledge, there is also a wealth of data collected in years of monitoring and assessment studies, as well as specific research projects. All of these resources are underutilized from a system perspective.
>
> Development of a simple, consistent, conceptual framework is a critical prerequisite for developing a watershed perspective in nitrogen cycling, identifying information gaps, synthesizing existing data, and proposing future programs. Such a framework must be able to cross spatial and temporal scales and serve as a guide wherein investigators can rapidly chart their position on the continuum, identify their research contribution, and determine gaps in nitrogen-cycling data at their site. A simple model based on the river continuum concept (Vannote and others, 1980).... can help develop an ecosystem-watershed approach, because it emphasizes linkages between the terrestrial and aquatic environment, upstream to downstream reaches, and freshwater to marine systems. Within this spatial continuum it also links hydrologic transport, retention (biological and physical), and biogeochemical transformation of contaminants.

The Thames Science Plan addresses these conceptual questions at the practical level of nutrient-related water-quality problems in the Thames River Basin. The Science Plan develops a watershed perspective on nutrient cycling, evaluates the potential of available data and assessments for further analysis and synthesis, identifies important gaps in information, and suggests studies designed to provide the information necessary for scientifically defensible management strategies.

To develop a conceptual model of the Thames River Basin, the watershed can be divided into subsystems for assessment and evaluation of hydrologic and water-quality dynamics. Interactions and influences among the subsystems can be further evaluated. Major components or subsystems of the Thames River Basin include small drainage basins with no point discharges, larger drainage basins with major streams that receive point discharges, impoundments, Norwich Harbor, and the Thames River Estuary. Small drainage basins can be further categorized as primarily forested, agricultural, or urban.

Maps showing land uses, water-quality conditions, or point discharge locations in the watershed present a static and sometimes composite picture of a dynamic environment. Processes that vary on a daily, seasonal, annual, or longer time frame operate throughout the watershed, mediating the timing and extent of nutrient-related effects on water quality. Thus, temporally variable processes need to be considered in evaluating nutrient sources and effects in all parts of the watershed. Further, biogeochemical processes occurring in streams, impoundments, and estuaries vary in three dimensions over varying time frames.

Several specific processes are important at multiple locations within the Thames Basin. Seasonal and annual streamflow variability is a major natural process that affects nutrient concentrations and loads throughout the watershed. Variable freshwater inflows affect water-quality conditions in impoundments, and streamflow regulation and dam releases affect downstream riverine reaches. Tidal cycles and seasonally variable freshwater inflows create a dynamic mixing environment in Norwich Harbor and the Thames River Estuary. Biogeochemical cycling of nutrients is an important process throughout the drainage basin.

The Freshwater Ecosystem

The freshwater ecosystem of the Thames River Basin is strongly influenced by nutrients from urban and agricultural areas, despite the fact that the drainage basin is primarily forested. The locations of urban areas and their associated point sources, in conjunction with the numerous impoundments in the Thames Basin, appear to have created a setting that magnifies the effects of nutrients on water-quality conditions.

Forested areas are present throughout the Thames River Basin. The most extensive forested areas are in the upper reaches of the Fenton, Mount Hope, and Natchaug River Basins in the central part of the Thames Basin, in the upper reaches of the Quinebaug River Basin in the vicinity of the border between Massachusetts and Connecticut, and in the upper reaches of the Five Mile, Moosup, and Pachaug River along the border between Connecticut and Rhode Island (figs. 1 and 2, table 1). The Nature Conservancy has identified the Quinebaug Highlands, a large block of intact forested land in the Fenton, Mount Hope, Natchaug, and Quinebaug River Basins, as an area of significant ecological value (The Nature Conservancy, no date). *Nutrients in freshwater in forested areas of New England are derived primarily from decomposition of plant and animal material and from atmospheric deposition. Stream concentrations of nutrients are low, and consequently streamflow from subbasins that are currently forested constitutes an important measure of dilution for downstream reaches with more developed land.*

Small agricultural areas are scattered throughout most parts of the Thames River Basin. More concentrated areas of agricultural land are along the central and lower reaches of the Quinebaug River Basin, the upper reaches of the Yantic Basin, and the lower reaches of the Shetucket Basin. A water-quality investigation of the major tributaries to Roseland Lake, near South Woodstock (fig. 1), concluded that nutrient concentrations were sufficient to support eutrophic conditions in the lake, and that the highest concentrations and loads were found in a tributary with more than one-third of its drainage area in agricultural uses (Kulp, 1991, p. 39). Preliminary results from an ongoing investigation of nutrients in the Quinebaug River basin indicate that agricultural land in the Little River subbasin may contribute substantially to the instream load of nutrients (M.J. Colombo, U.S. Geological Survey, written commun., 2003).

Urban areas, and consequently point discharges, are generally concentrated along major streams, primarily on or near the Willimantic and Shetucket Rivers in the Shetucket Basin, and the French and Quinebaug Rivers in the Quinebaug Basin (figs. 1 and 2). Water-quality monitoring for urban areas in Connecticut is generally encompassed by USGS monitoring stations on large streams that receive point discharges. Consequently, quantitative information on nonpoint nutrient sources in urban areas may be based on various estimates.

The possible importance of ground-water discharge as a source of nutrients in streams has not been examined extensively in the Thames River Basin. Studies in other areas of Connecticut have indicated that concentrations of nitrate nitrogen in ground water are substantially higher in agricultural and urban areas than in forested areas (Grady and Mullaney, 1998).

Understanding nutrient transport and processing in the Thames River Basin requires measurement and investigation of both large-scale and small-scale processes. Nutrients can be measured in terms of:

- instream *concentrations* and flow-adjusted concentrations,
- *concentration trends over time* (which can be unadjusted or flow-adjusted),
- *stream loads* for a particular time period, or
- *average drainage-basin yields* (total stream load divided by drainage area).

These measures provide a large-scale picture of nutrient sources and water-quality conditions in a drainage basin. *Unadjusted instream concentrations* provide a measure of the actual water-quality conditions that affect aquatic life habitat and biogeochemical processes. *Concentrations of many water-quality constituents vary with changes in stream discharge.* At stations that monitor streams in Connecticut with substantial urban influences, such as the Shetucket River at South Windham, nutrient concentrations are generally high at low streamflows and lower at high streamflows (Zimmerman and others, 1996, p. 102-103). This relationship reflects the relatively constant inputs from point discharges, which represent a larger percentage of stream discharge at low flows. In primarily forested drainage basins, nutrient concentrations are generally low at all ranges of streamflow, although concentrations may be higher during high flows because of increased nonpoint runoff. When used in *analyses of trends over time*, flow-adjusted concentrations can provide an indication of increases or decreases in nutrient sources. *Stream loads* of nutrients are a measure of the quantity of a constituent carried to a downstream location, such as an impoundment or an estuary, over a specific period of time. *Nutrient yields*, or loads per square mile of drainage area, provide a way to compare the loads from drainage basins of different sizes, or to compare incremental loads from drainage areas to successive downstream reaches along the same stream. *All of these measures are useful for understanding the sources and transport of nutrients on a large scale in a drainage basin.*

Biogeochemical processes and transformations at the microbial and molecular level have important effects on the cycling and transport of nutrients in streams and reservoirs. These processes include algal metabolism, nitrification and denitrification by bacteria, decomposition of organic matter, absorption, and other processes, which take place in the water column, in riparian zones and floodplains, at the sediment-water interface, and at interfaces between subsurface flow and sediments (the hyporheic zone). The scientific model of a stream and its transport of solutes has evolved from an older model of the stream as a pipe to a newer model of nutrient spiraling, in which there is periodic uptake and release of nutrients, and then further to a more current understanding of nutrient exchange (F.J. Triska, U.S. Geological Survey, oral commun., 2003). Under the nutrient exchange model, the "stream" is wherever the water is. The hyporheic zone is important as a zone of nutrient gradients, biologic processes, and hydrologic exchange between surface water and ground water. Lithologic and geomorphic factors affect the processes in this zone. The degree of surface-water penetration into the streambed, the presence or absence of oxygen, and the depth of the interface between aerobic and anaerobic conditions, are critical factors affecting nutrient processing in this zone. Nutrient processing at this level is not well understood in the Thames River Basin, but opportunities exist for applying research findings from other areas and planning local investigations that would supply needed information.

Drainage Basins that Receive Point Discharges

Although total phosphorus concentrations have declined in major streams of the Thames River Basin, eutrophic conditions and algal blooms persist annually during low-flow conditions in summer and fall on the Quinebaug River and its major tributary, the French River. Observations indicate that algal blooms typically occur first in upstream impoundments, including West Thompson Lake on the Quinebaug River and North Grosvenordale Pond on the French River, and then move downstream along the Quinebaug River, eventually affecting reaches as far downstream as Aspinook Pond and Jewett City.

Municipal wastewater-treatment facilities discharge effluent to the Shetucket and Quinebaug Rivers and their tributaries in Connecticut, and to the Quinebaug River and its tributaries in Massachusetts (Medalie, 1996) (fig. 4). Municipal wastewater return flows constituted approximately 1.3 to 2.4 percent of the annual mean stream discharges of the Quinebaug River, measured at USGS stations at Quinebaug and Jewett City, Connecticut, in the early to mid-1990's (Trench, 2000, table 8, p. 27). Wastewater return flows constituted a much larger percentage (9 to 27 percent) of annual mean streamflows in several more highly urbanized drainage basins in Connecticut, but not all of these streams experience the severe eutrophication problems that occur regularly on the Quinebaug River. Annual yields of total nitrogen and total phosphorus are generally higher in the Quinebaug River Basin than in undeveloped drainage areas of New England that have few or no point sources, but are substantially lower than in highly urbanized drainage basins in Connecticut that have major point sources (Trench, 2000, figs. 9-10, p. 33-36).

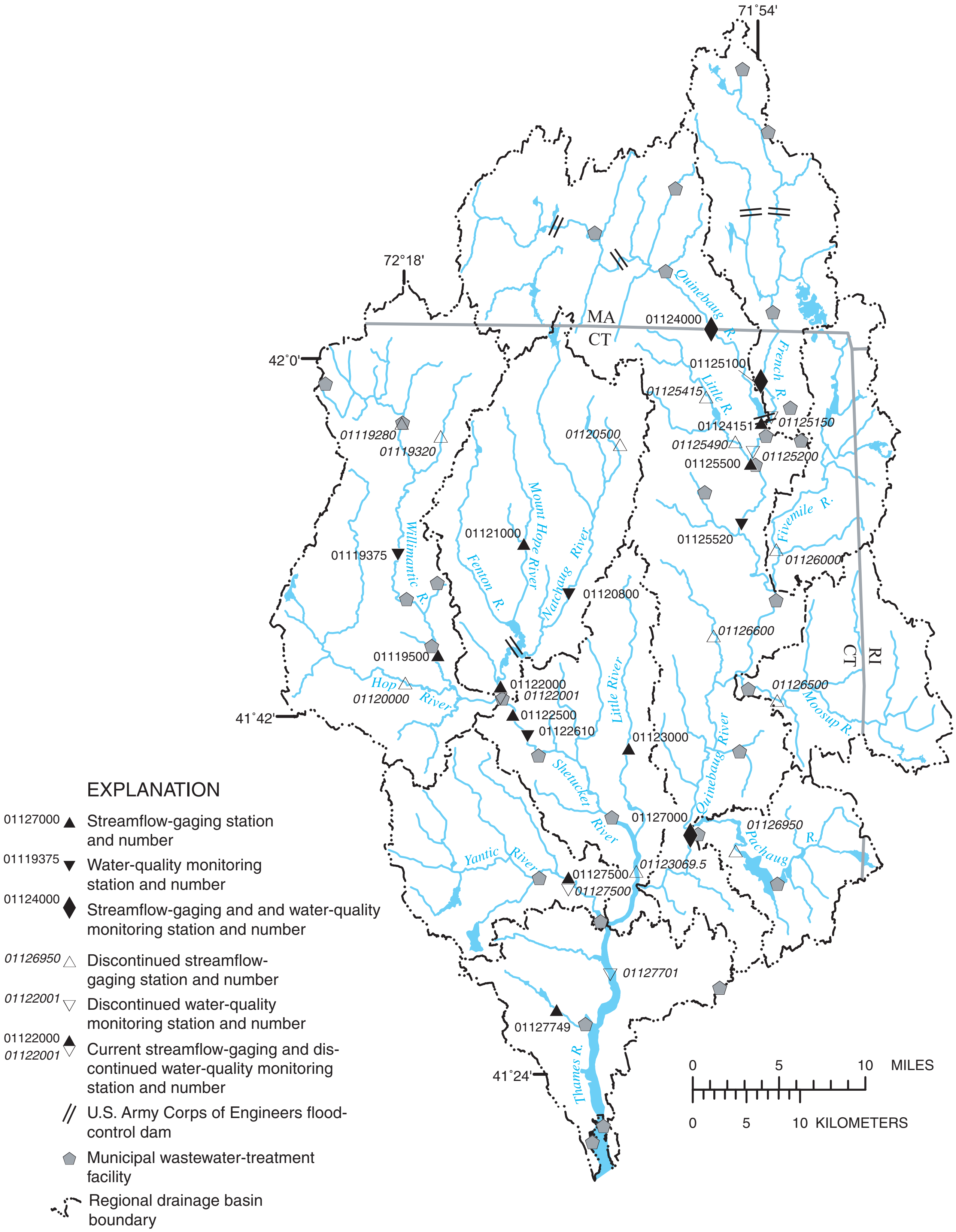

Figure 4. Map of Thames River Basin showing locations of U.S. Geological Survey streamflow-gaging stations and water-quality monitoring stations, municipal wastewater-treatment facilities, and U.S. Army Corps of Engineers flood-control dams. [Sources: U.S. Geological Survey, Connecticut Department of Environmental Protection, and Medalie, 1996.]

This apparent discrepancy between the relatively low magnitude of overall nutrient yields in the Thames River Basin and the severity of nutrient-related water-quality problems in specific locations suggests a need for further investigation into the sources of these problems. Several factors may contribute to the observed problems in freshwater streams. Although the basin is largely forested, most wastewater-treatment facilities are concentrated in limited areas along the major streams. Numerous impoundments, particularly along the Quinebaug River, result in low stream velocities and backwater areas, and create conditions that are favorable for nutrient and particulate retention and algal growth. Impoundments may store and release nutrients and algae under some conditions, and may function intermittently as "point sources" for downstream stream reaches. Seasonal low streamflows in summer and fall foster conditions favorable for algal growth, and regulation of streamflow may create critical lower streamflow periods within the seasonal low flow period.

Total phosphorus concentrations in many streams in Connecticut, including the Quinebaug and Shetucket Rivers, were significantly lower by the mid-1990s than in the 1970s and 1980s (Trench, 2000, table 12, p. 46). Historic phosphorus concentrations in these streams were very high as a result of wastewater discharges and phosphorus in detergents, and some of this phosphorus has been retained in streambed and reservoir sediments.

Sediments in streambeds and impoundments constitute a reservoir of nutrients that may continue to be recycled into the water column under some conditions. One of the key questions to be addressed in the Thames River Basin is the extent to which historic and recent sediments are an important contemporary source of nutrients.

Permits for wastewater-treatment facilities in Massachusetts currently limit phosphorus discharges seasonally, typically from about April to October. If winter wastewater discharges of phosphorus are flushed out of the drainage basin by winter stream discharges, then higher winter phosphorus concentrations do not fuel freshwater algal growth during the summer. However, if phosphorus discharged during the winter is retained in streambed sediments or impoundments, it may be available during the growing season. Consequently, *another important question is how the seasonally variable discharge of phosphorus from wastewater-treatment facilities may affect water quality.*

Impoundments

Variable streamflow and climatic conditions, streamflow regulation, variable wastewater loads, the nutrient content of sediments, circulation and nutrient cycling within reservoirs, water-quality conditions that vary in three dimensions, and the nutrient requirements of organisms are among the complex and dynamic factors that must be understood to manage nutrient-related water-quality problems in impoundments.

Dams and their impoundments are ubiquitous in the Thames River Basin, on small streams and major rivers. Types of dams and impoundments include historic mill dams and ponds, small hydroelectric power-generating facilities, and large flood-control reservoirs.

Several impoundments in the Quinebaug River Basin are classified as eutrophic, and do not support designated uses because of nutrient enrichment, algal growth, and low dissolved oxygen concentrations (table 2). The proportion of the Shetucket River Basin that is impounded is greater than the proportion of the Quinebaug. However, most of the Shetucket River system is deeper than the Quinebaug, water moves through the system more rapidly, and there are currently (2005) no eutrophication problems in the impoundments.

Although the major categories of nutrient sources are known for the Quinebaug River Basin, the relative importance of these sources has not been determined. Thornton (1990, p. 7) has noted that for reservoirs, distant sources may be more important than local sources:

> Reservoirs may receive only a small proportion of their total inflow as direct runoff from the adjacent watershed, with the majority of the water, nutrient, and sediment load entering from one or two major tributaries located a considerable distance from the dam.

In the case of Quinebaug River Basin impoundments, identification of appropriate nutrient management solutions would depend on determining the proportions of the nutrient load provided by sources in upstream drainage areas, sources in drainage areas adjacent to the impoundment, and the sediments in the impoundment itself. The answer to this question may differ for different impoundments, and the significance of the sources for a single impoundment may vary seasonally.

Sediment stored in impoundments may be a substantial source of phosphorus under some conditions. In a discussion of the phosphorus cycle in lakes, Wetzel (1983, p. 258) has noted that in oligotrophic lakes with a fairly uniform vertical distribution of oxygen concentrations, there is also very little variation in phosphorus concentration with depth. Conversely, in eutrophic lakes with low dissolved oxygen concentrations at depth, "there is a marked increase in phosphorus content in the lower hypolimnion, especially during the later phases of thermal stratification. Much of the hypolimnetic increase is in soluble phosphorus near the sediments." Exchanges across the sediment-water interface are regulated by numerous biogeochemical processes. One of the most important features is the oxygen content at this interface. The author cites studies and experiments that demonstrate the effectiveness of an "oxidized microzone in preventing significant release of soluble components from the interstitial waters of the sediments to the overlying water.... Phosphorus, in particular, was prevented from migrating upward" (Wetzel, 1983, p. 260-261). This "barrier" weakens as the oxygen concentration in water near the sediment interface declines, and as the redox potential decreases, constituents including alkalinity, carbon dioxide, ammonia, phosphate, iron, and manganese are released. The author further notes that "the depth of the sediment involved in active migration of phosphorus to the water is considerable" (Wetzel, 1983, p. 264).

West Thompson Lake is an impoundment on the Quinebaug River in northeastern Connecticut. The flood-control reservoir was constructed in 1965 and is managed by the U.S. Army Corps of Engineers. It has been classified as highly eutrophic (Healy and Kulp, 1995, p. 231), but water quality has improved to some extent in recent years. *The lake is impaired for purposes of aquatic life support and primary contact recreation, as a result of organic enrichment, excessive nutrients, low dissolved oxygen, and algal growth* (table 2) (Connecticut Department of Environmental Protection, 2004a, appendix B). Despite downward trends in total phosphorus concentrations and decreased loads of total phosphorus on the Quinebaug River upstream from West Thompson Lake (station 01124000; Trench, 1996, 2000), eutrophication and seasonal algal blooms persist in the reservoir, contributing to nutrient problems in the lower reaches of the Quinebaug and Thames Rivers.

West Thompson Lake stratifies weakly during the summer, and dissolved oxygen concentrations become depleted in areas where the lake is more than 12 feet deep (Healy and Kulp, 1995, p. 236, fig. 95). In the absence of a strong thermal gradient, rainfall may lead to mixing. This process may circulate phosphorus up from the hypolimnion, making it available to surface layers and downstream river reaches.

Preliminary interpretations from an ongoing study of nutrients in the Quinebaug River Basin indicate that West Thompson Lake may be a sink for phosphorus during most of the year, including the winter months; that is, phosphorus loads leaving the reservoir are less than phosphorus loads entering the reservoir. During some summer and fall months, however, the reservoir may become a source of phosphorus. *In some warm-weather months, phosphorus loads leaving West Thompson Lake exceed those entering the reservoir by a much greater amount than would be expected based on the increase in drainage area alone. Phosphorus stored in lakebed sediments may be the source of this increased load, with phosphorus released into the water column under certain conditions, fueling algal growth within the reservoir and in downstream reaches.*

Information from the ongoing Quinebaug nutrients study is insufficient to fully document the interpretation that reservoir sediments in West Thompson Lake are the source of phosphorus that drives eutrophic conditions. However, the results from this study, in conjunction with information in the scientific literature on phosphorus cycling, indicate that this is an important avenue for further investigation.

In evaluating the factors that lead to eutrophic conditions in West Thompson Lake and other reservoirs in the Quinebaug River Basin, a large suite of information needs to be considered. For example, West Thompson Lake has a generally north-south orientation, and prevailing winds in the summer are from the west and southwest. Prevailing winds may drive shallow surface-water layers to the northeast, allowing potentially phosphorus-rich bottom water to circulate closer to the surface in the southwest, near the reservoir outfalls (G. B. Noe, U.S. Geological Survey, oral commun., 2003).

Norwich Harbor and the Thames River Estuary

The Thames River Estuary forms at the confluence of the Shetucket and Yantic Rivers in downtown Norwich (fig. 1). Norwich Harbor occupies an area from the head of the estuary in downtown Norwich (referred to as the turning basin) to a point about a half mile downstream in the estuary. The Thames estuary itself is about 16 miles long from Norwich to Long Island Sound.

Low dissolved oxygen conditions are an annual problem in summer and early fall in the bottom waters of Norwich Harbor, and sometimes through a substantial portion of the water column (H.M. Weiss, Project Oceanology, *in* Thames Symposium, Connecticut Department of Environmental Protection, 2002c). Low dissolved oxygen conditions begin in Norwich Harbor early in the season, but eventually move downstream into the estuary, and may persist in the bottom waters of the estuary for several miles downstream. *Low dissolved oxygen is believed to be caused by oxygen demand from multiple sources, including organic load from tributary streams, sediment oxygen demand within Norwich Harbor, oxygen demand from the lower estuary, organic matter produced within the harbor as a result of nutrient enrichment from tributaries, and municipal wastewater effluent.*

Specific sources of organic matter, and sources of dissolved nutrients that contribute to the production of organic matter, include: freshwater phytoplankton produced in rivers upstream; upstream litterfall and soil-derived organic matter; actual phytoplankton production in the harbor; downstream algal biomass transported upstream by incoming tides; organic matter at the bottom of the harbor; and effluent from the Norwich wastewater-treatment facility. As organic matter is processed, decomposed, and cycled, these sources also may become sources of dissolved nutrients, which support further organic productivity. Participants in the Thames Symposium did not reach consensus on the relative importance of these factors in creating hypoxic conditions in Norwich Harbor (Connecticut Department of Environmental Protection, 2002c).

Nutrient loads cause direct and indirect responses in coastal ecosystems:

$$\textit{Nutrient loads} \rightarrow \textit{Filter} \rightarrow \textit{Direct Responses} \rightarrow \textit{Indirect Responses}$$

Each ecosystem has a "filter" that represents the complexity and characteristics of the individual system, and that mediates the specific responses to nutrient loading (J.E. Cloern, U.S. Geological Survey, oral commun., 2003). The component parts of the filter "include inherent physical and biological attributes that operate in concert to set the sensitivity of individual ecosystems to nutrient enrichment" (Cloern, 2001, p. 241). Important parts of the filter include tidal energy, horizontal transport processes that determine residence time, light limitation, and benthic grazing.

The physical attributes of Norwich Harbor, the Thames River Estuary, and the surrounding terrain constitute part of the "filter" that determines the response to nutrient loading (fig. 5). A saltwater wedge extends upstream underneath the mixed estuarine water and freshwater along the entire length of the Thames River under some conditions. The harbor and the long, narrow estuary are protected from wind mixing by steep hills, and this probably affects the magnitude of the salinity stratification. An enormous amount of energy is required to turn over the system. Density differences between top and bottom layers are large, resulting in a situation where there may be two almost uncoupled domains, with a sharp density discontinuity acting as a strong barrier to the exchange of water (J.E. Cloern, U.S. Geological Survey, oral commun., 2003). Consequently, residence time in the surface layer may be relatively short. *Seasonal and interannual streamflow variability, streamflow regulation, and tidal cycles create a complex hydrodynamic environment.* A bedrock sill downstream from the harbor also provides a barrier to mixing between the bottom waters of the harbor and the larger estuary.

Questions to be addressed regarding the physical processes in Norwich Harbor include circulation patterns in the harbor, solute residence times in the upper and lower layers of the water column, and the rate of exchange of water over the bedrock sill between the harbor and the larger estuary.

Alterations to the environment affect physical processes and water quality in Norwich Harbor and the Thames River Estuary, including large areas of impervious surfaces, riparian urban areas and industries, engineered embankments, and dredging within the estuarine channel. The circulation in some small streams, tidal creeks, and embayments may be constricted by causeways for roads and railroads along the length of both the eastern and western shores of the Thames River Estuary.

In evaluating the potential results that can be achieved in Norwich Harbor and the upper Thames River Estuary by managing nutrients, it may be important to consider the question of whether the system was historically anoxic (J.E. Cloern, U.S. Geological Survey, oral commun., 2003). Anecdotal information indicates that shellfish were formerly present farther upstream in the Thames River Estuary than they are now, indicating that hypoxia from Norwich Harbor has moved downstream. Accurate historical information may contribute to an understanding of whether the hypoxic conditions are entirely the result of human alterations to the environment, or whether the natural setting of the harbor and estuary leads to these conditions under some circumstances.

In the harbor and estuary as in the upstream freshwater reaches, small-scale processes are important as well as large-scale processes such as estuarine circulation. All factors need to be understood and considered, including, for example, microbial processes that affect nutrient cycling, changes in nutrient ratios that determine the composition of phytoplankton communities, and changes in water transparency that affect plant communities. *Chemical gradients from freshwater to saltwater create a succession of biological communities and contribute to death and decomposition of these communities.*

Review of the Historical Database for the Thames River Basin

The historical database for the Thames River Basin is substantial. Monitoring and interpretive programs by state and federal agencies have focused primarily on the freshwater system. Academic institutions have conducted substantial research in both the estuarine and freshwater systems.

U.S. Geological Survey

USGS streamflow-gaging stations and water-quality monitoring stations in the Thames River Basin have record lengths ranging from 5 to 86 years for discharge and 1 to 38 years for water quality (table 5, fig. 4). Several locations have been monitored for nutrient constituents since the early- or mid-1970s. Information on nutrient concentrations, including summary statistics, for several Thames monitoring stations has been compiled as part of statewide or regional water-quality investigations (Healy and others, 1994; Zimmerman and others, 1996, table 25, p. 139-146; Jonathan Morrison, U.S. Geological Survey, written commun., 2004). Trends in nitrogen and phosphorus constituents have been analyzed for several stations in the Thames Basin (Trench, 1996, app. 2, p. 102-106, app. 3, p. 140-145; Zimmerman and others, 1996, p. 78-79; Trench, 2000, table 12, p. 46; Colombo and Trench, 2002).

Nutrient load-estimation programs typically require continuous (daily) streamflow data and periodic water-quality data for estimating annual or monthly constituent loads. The current (2004) USGS monitoring network includes nine continuous-record stations in the Thames Basin (table 5). Of these, only two stations (Quinebaug at Quinebaug and Quinebaug at Jewett City) have long-term water-quality data, and a third (Quinebaug at Putnam) has a recently established (1999) water-quality monitoring program. At a fourth location, a drainage-area correction can be used with the discharge data for the Shetucket River near Willimantic to create a daily discharge record for the long-term water-quality data for the Shetucket River at South Windham. For recent years, six stations in the monitoring network have discharge records only, and four stations have water-quality data only (table 5, fig. 4). Additional stations are partial-record stations for discharge, and consequently their records are not sufficient for use in load-estimation programs that require continuous discharge data. Annual nitrogen or phosphorus loads have been estimated for variable periods of record for several stations that have continuous discharge records (Trench, 2000; Mullaney and others, 2002; M.J. Colombo, U.S. Geological Survey, written commun., 2003).

Figure 5. Map of Thames River Estuary showing surrounding terrain in shaded relief.

Table 5. Current and discontinued U.S. Geological Survey streamflow-gaging (discharge) and water-quality monitoring stations in the Thames River Basin, Connecticut.

[Period of record listed for water-quality monitoring stations generally refers to the maximum record and may not apply to all constituents. Periods of record include partial years. Discharge methods: I, instantaneous at time of water-quality measurement; C, continuous record water-stage recorder; DAC, drainage-area correction; --, not applicable]

U.S. Geological Survey station		Drainage area (in square miles)	Discharge		Water quality
Number	Name		Method	Period of record	Period of record
01119280	Willimantic River at Stafford Springs, Conn.	52.9	C	1963-67	--
01119320	Roaring Brook near Stafford Springs, Conn.	14.7	C	1961-66	--
01119375	Willimantic River at Merrow, Conn.	94.0	I (DAC)	--	1974-04
01119500	Willimantic River near Coventry, Conn.	121	C	1931-04	1956-57, 1963-64, 1975-80
01120000	Hop River near Columbia, Conn.	73.9	C	1932-71	--
01120500	Safford Brook near Woodstock Valley, Conn.	4.16	C	1950-81	--
01120800	Natchaug River at Chaplin, Conn.	67.9	I	--	1962-64, 1995-04
01121000	Mount Hope River near Warrenville, Conn.	28.6	C	1940-04	1959 (WSP 1641)
01122000	Natchaug River at Willimantic, Conn.	174	C	1930-89, 1995-04	1954, 1958, 1968
01122001	Nachaug River at Willimantic, Conn.	174	I	--	1974-80
01122500	Shetucket River near Willimantic, Conn.	404	C	1933-04	1957, 1968-74
01122610	Shetucket River at South Windham, Conn.	408	I (DAC)	--	1974-04
01123000	Little River near Hanover, Conn.	30.0	C	1951-04	NS
011230695	Shetucket River at Taftville, Conn.	512	C	1989-97; 2001	--
01124000	Quinebaug River at Quinebaug, Conn.	155	C	1931-04	1953, 1960, 1963, 1969, 1980-03
01125100	French River near North Grosvenordale, Conn.	101	I/C	2000-04	1991-04
01125150	French River at Mechanicsville, Conn.	107	I	--	1962-63; 1974-91
01125200	Quinebaug River at Putnam, Conn.	288	I (DAC)	--	1962; 1974-80
01125415	Muddy Brook near Woodstock, Conn.	20.2	C	1979-83	--
01125490	Little River at Harrisville, Conn.	35.7	C	1961-71	--
01125500	Quinebaug River at Putnam, Conn.	328	C	1929-69, 1995-04	1955, 1957-58, 1959, 1960, 1962, 1970, 1972, 1999-04
01125520	Quinebaug River at Cotton Bridge Road near Pomfret Landing, Conn.	342	I (DAC)	--	1974-80, 1995-04
01126000	Fivemile River at Killingly, Conn.	57.8	C	1938-71	--
01126500	Moosup River at Moosup, Conn.	83.2	C	1933-71	--
01126600	Blackwell Brook near Brooklyn, Conn.	16.8	C	1964-76	--
01126950	Pachaug River at Pachaug, Conn.	53.2	C	1961-75	--
01127000	Quinebaug River at Jewett City, Conn.	713	C	1918-04	1956, 1968-04
01127500	Yantic River at Yantic, Conn.	89.3	C	1930-04	1958, 1968-80
01127701	Thames River near Mohegan, Conn.	1,382	I	--	1963; 1974-91

A study of nutrient concentrations and loads in the Quinebaug River Basin included additional sampling at long-term water-quality stations, as well as short-term project stations (M.J. Colombo, U.S. Geological Survey, written commun., 2003). Short-term stations were monitored on the main stem of the Quinebaug River as well as on the major tributaries (fig. 6), and were sampled from October 1999 to September 2001. Short-term sampling has enabled better definition of water-quality conditions in tributary streams, as well as comparisons of nutrient concentrations in tributaries and the main stem of the Quinebaug River.

Information compiled in the above-mentioned studies on annual stream nutrient loads, and basin nutrient yields per square mile, provides an opportunity for additional analysis and interpretation. Nutrient yield information for drainage basins within the Thames Basin and elsewhere in Connecticut can be used, in conjunction with additional targeted monitoring and GIS analysis of subbasin land uses, to achieve a better definition of nutrient yields in subbasins throughout the Thames Basin.

Water-quality characteristics, including water-quality profiles, have been reported for 18 lakes and ponds in the Thames River Basin in a statewide reconnaissance of lakes and ponds for the period 1989-91 (Healy and Kulp, 1995). A study of seasonal water quality, nutrient cycling, and sediment phosphorus content in West Thompson Lake is currently (2005) in progress (Jonathan Morrison, U.S. Geological Survey, written commun., 2004).

Connecticut Department of Environmental Protection

The CTDEP Bureau of Water Management conducts several ongoing statewide monitoring programs, as well as special projects and intensive surveys, that provide data on water-quality conditions, aquatic community composition, and related information for numerous locations in the Thames River Basin (fig. 7). Interpretation of this information in conjunction with other sources of water-quality data would lead to a more complete understanding of aquatic conditions, and may lead to correlations that could be applied to estimate likely water-quality conditions in unmonitored areas.

The Ambient Biological Monitoring Program "characterizes water quality by evaluating the biological integrity of resident communities of aquatic organisms" (Connecticut Department of Environmental Protection, 1999, app. D, p. 8). The program has been conducted by the CTDEP Bureau of Water Management since the early 1970s, and has focused primarily on the benthic invertebrate community of wadeable streams. Physical and chemical analyses are also conducted quarterly. CTDEP adopted a rotating basin approach for this program in the late 1990s, to cover all basins in the state periodically and more comprehensively (Connecticut Department of Environmental Protection, 1999, p. 7-9). This program represents a large resource of data on aquatic community composition for stream reaches of the Thames Basin. The program includes 72 locations in the Thames River Basin (fig. 7). Measures of the quality of aquatic communities are summarized for 54 of these locations for 1999 to 2000 in the 2002 305 (b) report (Connecticut Department of Environmental Protection, 2002b, Appendix H). Earlier monitoring data are summarized in some previous 305 (b) reports, and extensive biological data for 1976-85 are tabulated in Healy and others (1994).

The Probabilistic Monitoring Program was initiated in 2001 as part of an effort to assess 100 percent of the wadeable streams in Connecticut (M. Beauchene, Connecticut Department of Environmental Protection, oral and written commun., 2003). A grid has been used to create a random sampling network; 60 sampling locations have been selected statewide, 14 of which are in the Thames River Basin (fig. 7). Data collected at these stations include fish, macroinvertebrate, and periphyton community information, as well as quarterly physical and chemical data from grab samples.

A fish community study conducted by CTDEP included almost 1,000 stations statewide, with 289 stations in the Thames River Basin (fig. 7) (M. Beauchene, Connecticut Department of Environmental Protection, written commun., 2003). The study focused on wild trout populations and documented fish community structure, but also collected macroinvertebrate data and limited physical and chemical data.

Narrative summaries of aquatic vegetation for 18 lakes and ponds in the Thames River Basin are included in a statewide reconnaissance of water-quality characteristics of lakes and ponds for the period 1989-91 (Healy and Kulp, 1995).

The CTDEP conducted a monitoring survey of the Thames River Estuary on five dates in the summers of 2000 and 2001 (M. Beauchene, Connecticut Department of Environmental Protection, written commun., 2002) (fig. 8). Water-column samples at five stations were collected at the surface, at a depth of 4 meters, and 1 meter from the bottom. Field measurements included transparency and physical and chemical profiles. Laboratory measurements included nutrients and chlorophyll *a*.

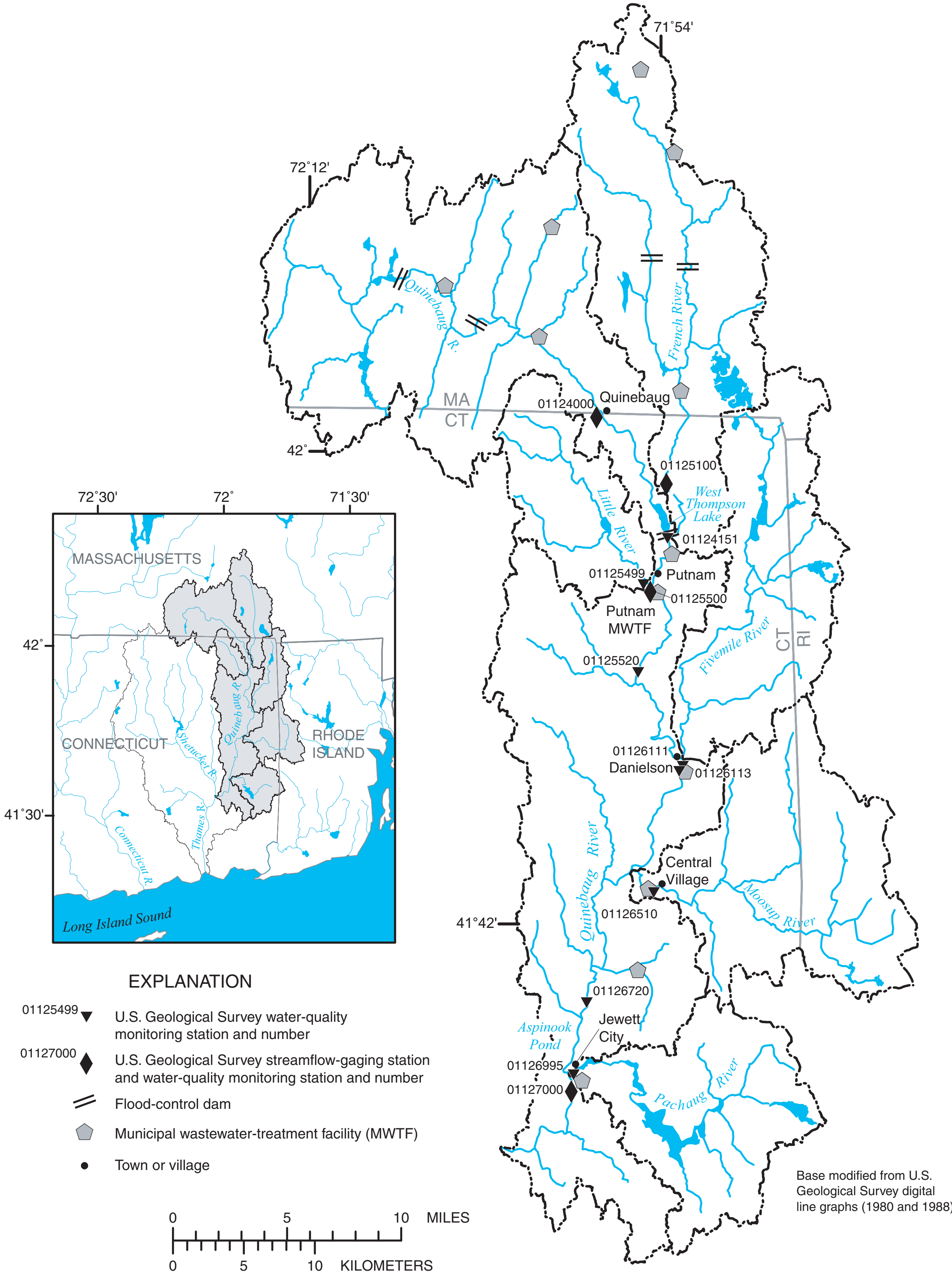

Figure 6. Map of the Quinebaug River Basin showing U.S. Geological Survey water-quality monitoring stations used in the Quinebaug nutrients project, 1999-2001.

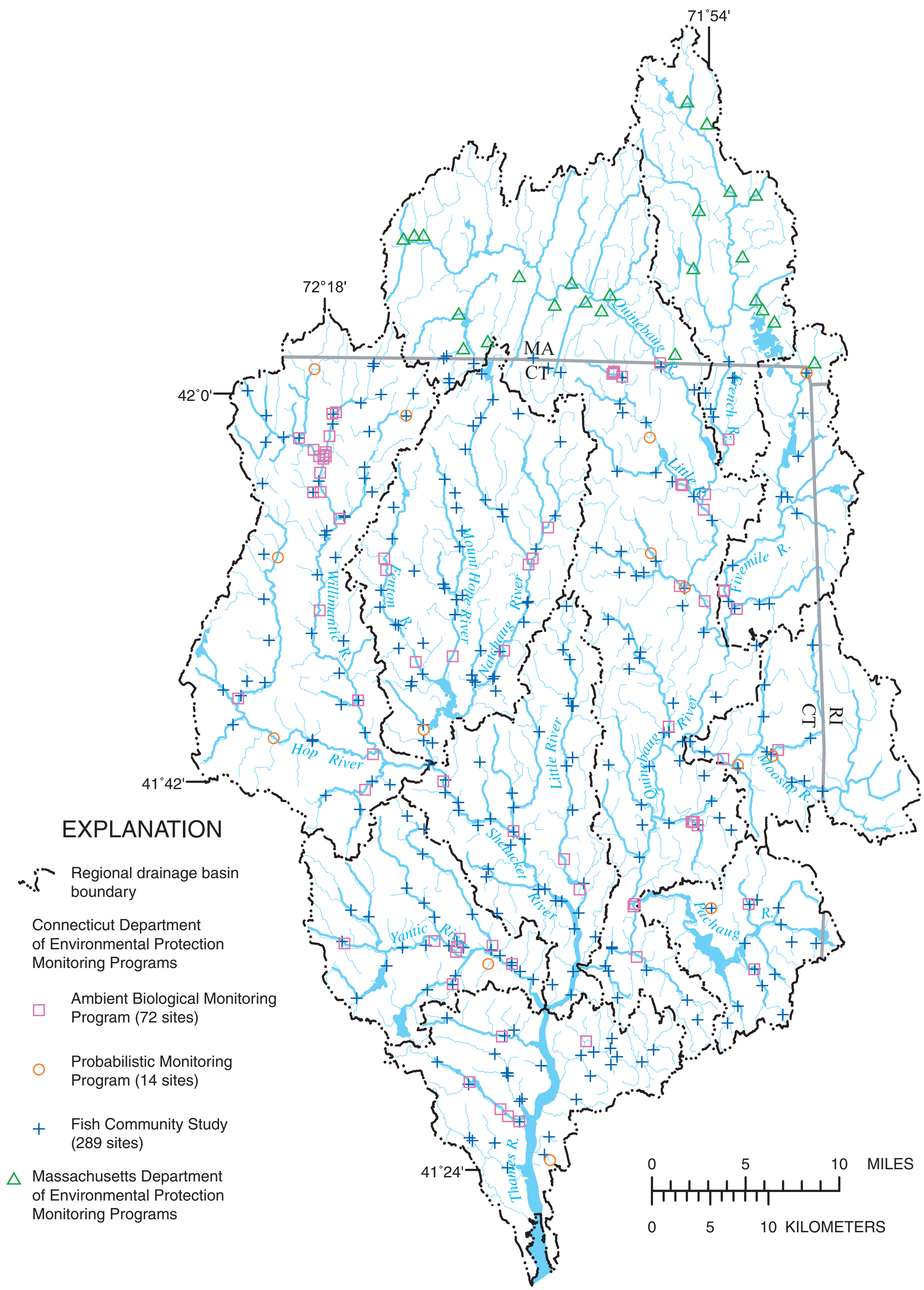

Figure 7. Map of Thames River Basin showing monitoring locations for Connecticut and Massachusetts Department of Environmental Protection water-quality programs. Sites for the Ambient Biological Monitoring Program are from 1999-2000 and earlier; sites for the Probabilistic Monitoring Program were initiated in 2001; sites for the Fish Community Study are from 1988-1994. [Sources: Michael Beauchene, Connecticut Department of Environmental Protection, oral and written commun., 2003; Therese Beaudoin, Massachusetts Department of Environmental Protection, oral and written commun., 2004.]

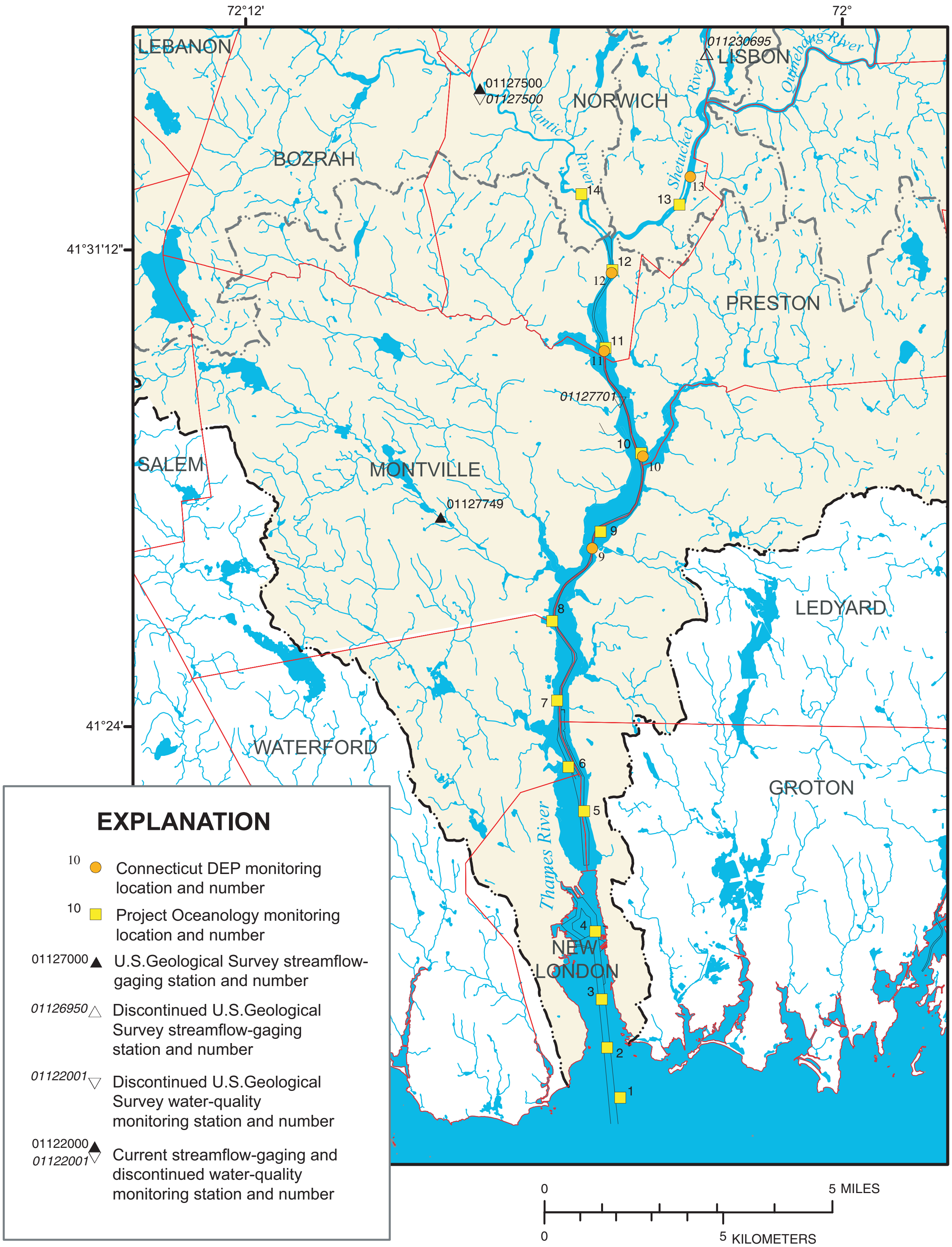

Figure 8. Map of Thames River Estuary showing monitoring locations for several programs.

U.S. Army Corps of Engineers

Water-quality information for several locations within the project areas of U.S. Army Corps of Engineers (Corps) flood-control reservoirs in the Thames River Basin in Massachusetts and Connecticut is available in electronic format from 1989 to the present (T.G. Barker, U.S. Army Corps of Engineers, written commun., 2003) (fig. 9). Data for water-quality sampling sites may include selected physical and chemical parameters, nutrients, bacteria, chlorophyll *a*, trace metals, organic chemicals, and weather.

The Corps collects water-quality samples in alternate years in about a half a dozen locations at West Thompson Lake. Data are presented in the Corps annual report. Water-quality information for 1971 to the present is available in paper files at the West Thompson Lake office. Information has not been synthesized for a total picture of lake functioning.

The Corps has published reports on Priority Pollutant scans of reservoir sediment for Mansfield Hollow Lake, Mansfield, CT (2000, electronic); Hodges Village Dam, Oxford, MA (1999, electronic); Buffumville Lake, Oxford, MA (1999, electronic); and West Thompson Lake, West Thompson, CT (1994, paper), and a fish contamination study for West Thompson Lake (1995, electronic). Although not directly related to the nutrient questions addressed in this Science Plan, this information may be relevant to water-resource managers for implementation of management strategies for nutrients that involve treatment, disturbance, or removal of reservoir sediment.

Massachusetts Department of Environmental Protection

The Massachusetts Department of Environmental Protection (MADEP) is responsible for monitoring the waters of the Commonwealth, identifying those waters that are impaired, and developing a plan to bring them back into compliance with state standards (Massachusetts Department of Environmental Protection, 2002, p. 4). The MADEP Division of Watershed Management generally monitors each drainage basin every 5 years as part of the 305 (b) assessment process (fig. 7). Stream monitoring is generally conducted monthly from April to October, with some diurnal sampling to obtain the nighttime oxygen sag point. Habitat data are also collected. Lakes are monitored and assessed under this program for nutrient-related physical and chemical constituents and nuisance aquatic plants (Massachusetts Department of Environmental Protection, 2002, p. 4).

The Central Regional Office of MADEP conducts the SMART Monitoring Program (Strategic Monitoring and Assessment for River Basin Teams) (T. Beaudoin, Massachusetts Department of Environmental Protection, oral commun., 2003). Two stations in the Quinebaug River Basin and one station in the French River Basin have been sampled approximately every other month under this program since March 1999, and a third station in the Quinebaug Basin was added in 2003. The monitoring program includes measurement of field parameters and laboratory analysis of nutrients and related constituents. Visual habitat indicators are also assessed. The program is designed to evaluate long-term status and trends.

Other Sources of Information

Sources of additional data and interpretations for the freshwater and estuarine portions of the Thames River Basin include academic research, private sector investigations, and citizen organizations. A review of these sources is beyond the scope of this Science Plan, but they constitute a substantial resource of information, and could be consulted and considered in the design of any future monitoring, data synthesis, interpretive, and modeling efforts.

Selected research programs and studies were summarized or reviewed as part of the Thames Symposium in 2002 (Connecticut Department of Environmental Protection, 2002c). The Thames Symposium document includes interpretations and reviews of information on water quality and algal conditions in freshwater streams and the Thames River Estuary, as well as summaries and reviews of modeling efforts for the whole basin and the estuary. Of particular interest is a study of water quality in the Thames River Estuary conducted by Project Oceanology (H.M. Weiss, Project Oceanology, *in* Thames Symposium, Connecticut Department of Environmental Protection, 2002c). The Project Oceanology study provides profiles of dissolved oxygen and salinity for 12 locations in the Thames River Estuary from May to December in 1997 (fig. 8).

Academic institutions conduct extensive research in the freshwater and estuarine portions of the Thames River Basin. These research programs provide information that can be used to support the applied science and management needs of water-quality restoration efforts in the Thames River Basin. The Cornell University Department of Natural Resources is conducting an ecohydrology study in the upper Quinebaug River Basin, focusing on fish community habitat, stream characteristics, and streamflow issues (Parasiewicz and Gallagher, 2002). The University of Massachusetts at Dartmouth Department of Civil and Environmental Engineering has prepared a report on the hydrology and hydraulic characteristics of lakes, ponds, and reservoirs in the upper Quinebaug River Basin (Hydrology and Water Resources Group, 2001). The report encompasses the drainage area of the Quinebaug River to its confluence with the French River, downstream from the outlet of West Thompson Lake in northeastern Connecticut. Ongoing research topics in the University of Connecticut Department of Marine Sciences include estuarine circulation, phytoplankton, and other areas of fundamental knowledge that are necessary to understand the water-quality problems of the Thames River Estuary.

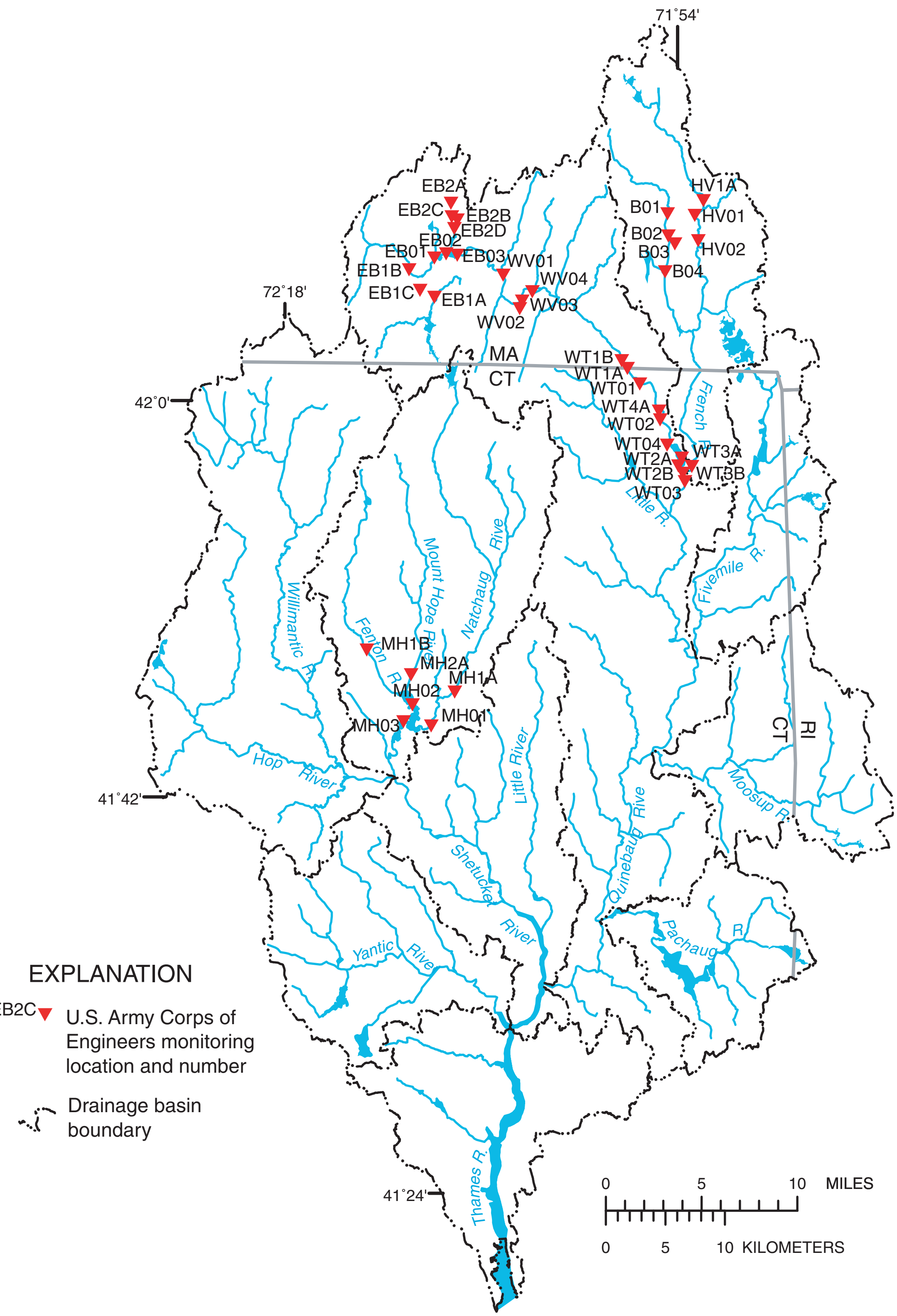

Figure 9. Map of Thames River Basin showing water-quality sampling locations for U.S. Army Corps of Engineers flood-control reservoirs.

Citizen groups in the Thames River Basin conduct volunteer monitoring programs through the CTDEP Rapid Bioassessment Program and other private, nonprofit programs. The Streamwalk Program, an interagency program supported by the CTDEP and other state and local agencies, has relied heavily on volunteers for collecting specific information about riparian and water-quality conditions along substantial reaches of freshwater streams in the Thames River Basin. Other private nonprofit groups have or are planning volunteer monitoring programs. Opportunities exist for integrating these programs within the larger agency objectives of monitoring to fulfill specific information needs.

Assessment of Information Needs

An important part of the process for water-quality management in the Thames River Basin is to evaluate and identify, on an ongoing basis, the measurements and monitoring data necessary to understand and determine the occurrence, sources, quantities, transport, fate, and cumulative effects of nutrients throughout the watershed. Carefully planned acquisition of fundamental data and related interpretations would eventually support the higher-level studies that are needed to understand and manage nutrient-related water-quality problems.

Scientific researchers have emphasized that it is necessary to invest time in understanding how individual ecosystems work (J.E. Cloern, U.S. Geological Survey, oral commun., 2003). It is not accurate, or practical, to expect that one system description and one management strategy will work for all systems. *The specific characteristics of the watershed, estuary, or ecosystem must be understood.*

Numerous water-quality monitoring projects, interpretive studies, and modeling projects have been conducted in the freshwater and estuarine portions of the Thames River Basin, often in support of management efforts to assess and control nutrient-related water-quality problems. *As detailed in the summary papers of the Thames Symposium, the more complex modeling studies have almost universally suffered from the lack of one or more forms of critical data* (Connecticut Department of Environmental Protection, 2002c). Attempts at higher-level interpretive and modeling studies are fueled by the immediate management need to understand and address complex problems. Often, however, study results fall short of expectations and do not meet articulated management goals because available data are insufficient to produce reliable, consistent, and scientifically defensible results. Data may be considered insufficient for several reasons. Necessary parameters may not have been measured, or key locations may not have been sampled. The frequency or timing of sampling may be inadequate for understanding the processes being studied. Sampling may have discontinuities in time or may be of insufficient duration. Data on vertical variability in water quality and circulation may be unavailable for layered systems.

The Thames Water-Quality Symposium (Connecticut Department of Environmental Protection, 2002c) provided a forum for summarizing past work and assessing future information needs in the Thames Basin. Recommendations from the Symposium, which focus on routine monitoring, research investigations, and modeling, were summarized and prioritized as part of the Symposium report (fig. 3).

The assessment of information needs in the Thames Science Plan has included a review of the recommendations from the Thames Symposium, and an evaluation of the data and information necessary to support investigation of progressively more complex questions. The Science Plan focuses on acquisition of fundamental data, interpretive studies, and simple modeling approaches, because the information from these types of studies is necessary to support the more complex modeling approaches that may eventually be implemented.

Scientific investigations provide information for understanding nutrient-related water-quality problems in freshwater and estuarine ecosystems. This information can be used to support management decisions and actions to address these problems (fig. 10). The process of defining information needs, conducting investigations, interpreting results, and identifying additional needed studies is an iterative process that leads to an integrated understanding of watershed processes. Likewise, the adaptive management process evaluates scientific information, uses this information to design management actions to address water-quality problems, and determines additional information needs. Linkages between the scientific and management processes are shown in figure 10. A generalized decision point for management actions is shown in figure 10; however, management decisions and actions can take place at any point in this process.

Scientific information needs for nutrients in freshwater and estuarine ecosystems are complex, and include several categories of information (figs. 11 and 12). Understanding and management of freshwater and estuarine systems require information on nutrient sources and loads, nutrient cycling processes, nutrient circulation and transport, effects of streamflow or tidal variability, algal population dynamics, and the physical, chemical, and biological conditions that lead to algal blooms in freshwater and hypoxia in an estuary. These building blocks of information can lead to an integrated understanding of the causes and development of nutrient-related water-quality problems (figs. 11 and 12). A generalized sequence for scientific investigations to fulfill these information needs is shown in figures 11 and 12, with the more fundamental information categories near the top of each figure and the more complex, integrated, and interdisciplinary categories at the bottom of each figure. In practice, specific scientific studies are likely to address more than one of the information categories shown in figures 11 and 12.

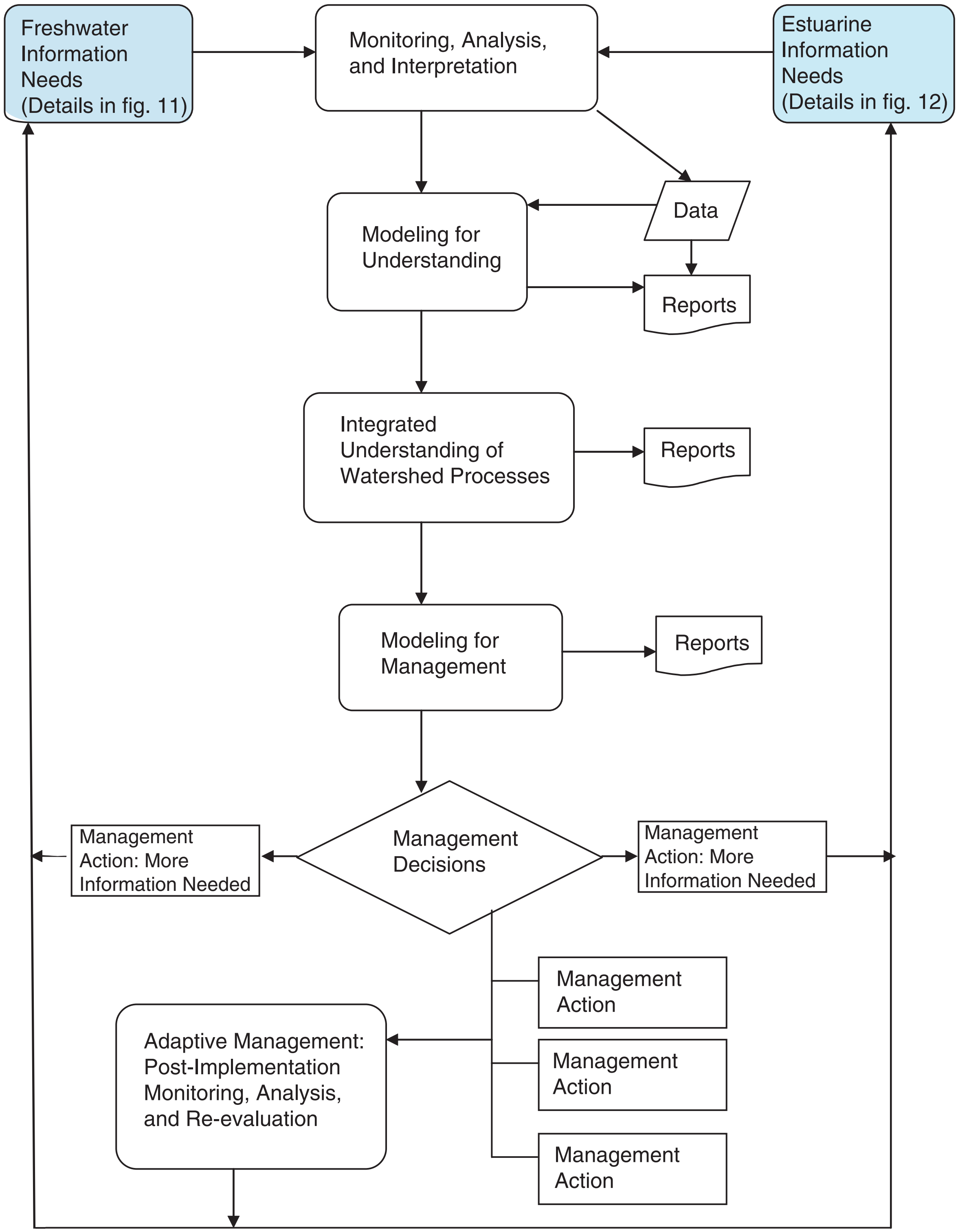

Figure 10. Overview of steps that could assist water-resource managers in understanding and management of nutrient-related water-quality problems in the Thames River Basin.

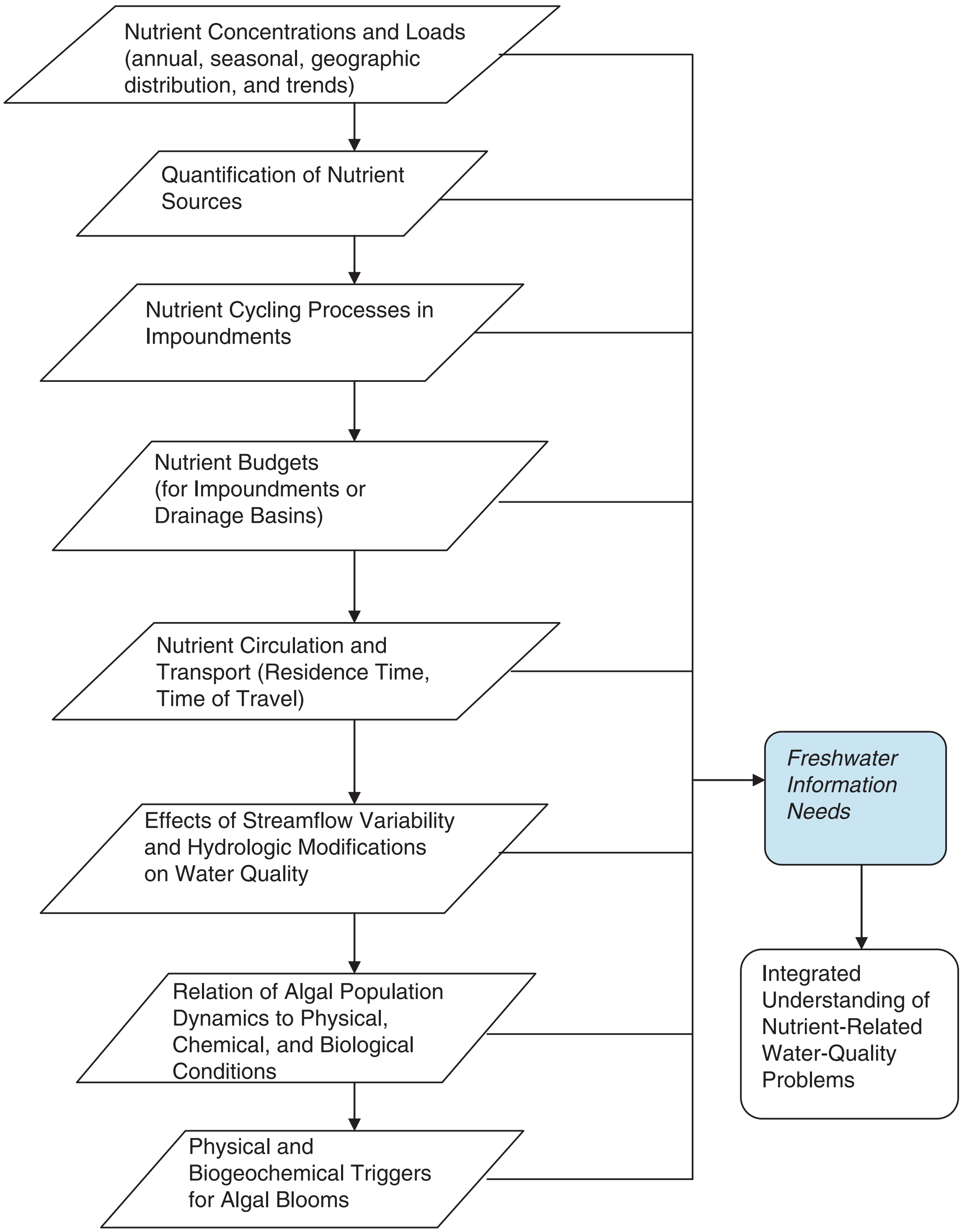

Figure 11. Major categories of scientific information and suggested sequence of investigations to fulfill freshwater information needs in the Thames River Basin. All the information categories listed may include elements of field data collection, interpretation of existing information, identification of modeling needs, and modeling.

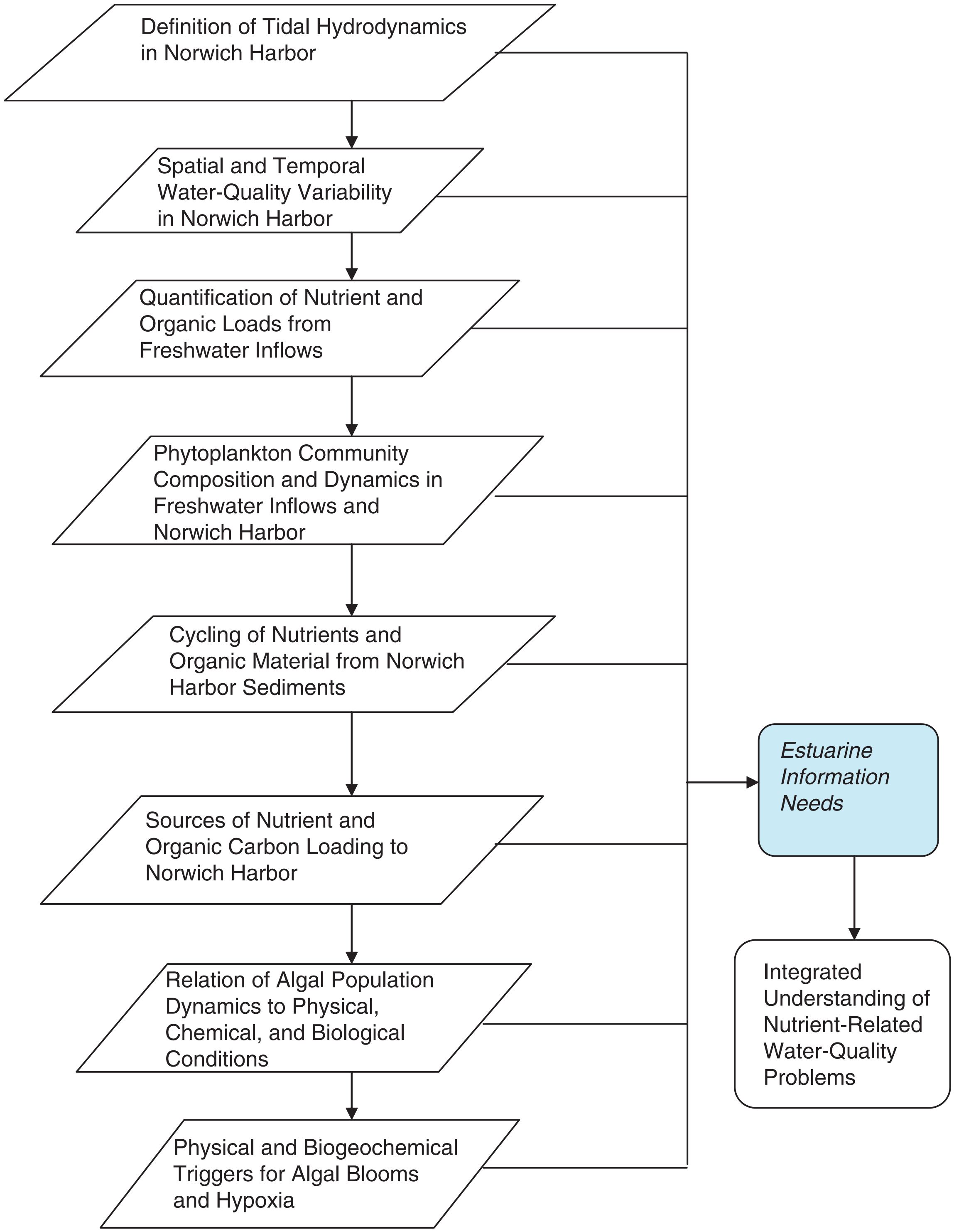

Figure 12. Major categories of scientific information and suggested sequence of investigations to fulfill estuarine information needs in the Thames River Basin. All the information categories listed may include elements of field data collection, interpretation of existing information, identification of modeling needs, and modeling.

The following sections discuss scientific information needs for addressing nutrient-related water-quality problems in ponds and impoundments, freshwater streams, and estuarine areas. The categories of scientific information needs shown in figures 11 and 12 form a basis for this discussion. Although the discussion of ponds and streams focuses on phosphorus, it is assumed that nitrogen would be included in most studies to provide information that would eventually be needed for estuarine areas. The conceptual model of the Thames River Basin has been used to formulate basic scientific questions for these three categories of water bodies. These questions are posed as a series of hypotheses, along with a summary of the data needed to address each hypothesis. As studies are completed, and new information is integrated into the conceptual model, new hypotheses and data needs can be formulated.

Ponds and Impoundments

Research on nutrient cycling attempts to fill in a conceptual model of the system by asking these questions: How does phosphorus (or nitrogen) cycle through the components of the ecosystem? How much phosphorus do different components of the ecosystem store? What are the magnitudes of phosphorus fluxes between the components? (G.B. Noe, U.S. Geological Survey, oral commun., 2003). Answering these questions builds information necessary for developing a nutrient budget for an ecosystem such as West Thompson Lake. Different components of the ecosystem may control the short-term and long-term flow of phosphorus. *Development of nutrient budgets for impoundments could meet an important information need, because impoundments play an important role in the streamflow characteristics and water-quality conditions of the Quinebaug River Basin.*

West Thompson Lake

Information needs for West Thompson Lake illustrate the dual nature of the needs for understanding watershed processes at large and small scales. Information needed at the large scale includes estimates of phosphorus loads on a year-round basis for municipal wastewater-treatment facilities in Massachusetts. Quantifying this large phosphorus load and determining its seasonal distribution is important to a full understanding of nutrient dynamics in the reservoir, and development of a nutrient budget. Quantification of nonpoint sources is also needed. At the molecular or particulate scale, information is also needed on the physical, chemical, and biological processes operating at the sediment-water interface and within the reservoir sediments, and the seasonal variability in these processes.

Objectives of an ongoing (2003–05) USGS project, “Phosphorus Budget for West Thompson Lake” are (1) to develop a conceptual model of phosphorus cycling; (2) to estimate nonpoint loads of phosphorus between USGS streamflow-gaging station 01124000 and West Thompson Lake; and (3) to estimate the mass of phosphorus stored in lakebed sediments. A temporary streamflow-gaging and water-quality monitoring station (01124130) has been installed on the Quinebaug River at Red Bridge Road upstream from the reservoir. Information collected at this location would help define nonpoint loads between the reservoir and the long-term station on the Quinebaug River at Quinebaug (01124000) and would support development of a nutrient budget for the reservoir itself. Water-quality sampling includes monthly, weekly, or continuous monitoring at locations within the reservoir and on the Quinebaug River upstream and downstream from the reservoir (stations 01124130 and 01124151). Constituents that are measured or analyzed include nutrients, chloride, and a group of physical, chemical, and biological parameters related to algal growth and metabolism. Initial project funding supported water-quality sampling from June to November 2003. Year-round sampling is considered to be necessary for development of annual and seasonal phosphorus budgets, and in the fall of 2003, CTDEP allocated the resources to continue monthly sampling through September 2004. Continuity of sampling represents an opportunity to maximize the utility of information collected in the current study for future purposes.

Several additional forms of data collection or analysis would facilitate understanding of nutrient dynamics and development of nutrient budgets for West Thompson Lake. Because of the degree of streamflow regulation upstream from the Quinebaug River station at Quinebaug (01124000), it may be difficult to develop a reliable extrapolation between that station and the temporary station at Red Bridge Road (01124130). Gates in the West Thompson dam may release water from different levels in the lake at different times. Information on the timing and depth of lake water releases needs to be reviewed relative to water-quality information and the timing of algal bloom development in downstream reaches. An opportunity may exist to improve water quality through flow management. As part of the interpretation of data in the West Thompson Lake project, it will be important to determine if the data collected are sufficient to verify a seasonal signal in the outflow of phosphorus from West Thompson Lake, before discontinuing water-quality data collection at temporary stations.

Other Impoundments

Lakes impounded by flood-control dams and other dams in Massachusetts that are upstream from West Thompson Lake, as well as flood-control and other dams in the French River Basin, may also act as sinks for phosphorus, or as seasonal phosphorus sources, depending on local conditions. Information on other impoundments needs to be evaluated as part of the effort to understand seasonal nutrient loads to West Thompson Lake from the Quinebaug River and to the French River. Interpretations and findings from studies of West Thompson Lake could contribute to the understanding of other impoundments, and to the design of studies specific to other impoundments.

Reservoir Hypothesis 1: West Thompson Lake, and possibly other impoundments in Massachusetts and Connecticut, change seasonally from a phosphorus sink in cold weather to a phosphorus source during the growing season.

Data Needed to Address Hypothesis: Annual and seasonal quantification of nutrient concentrations, sources, and loads upstream and downstream from impoundments.

Reservoir Hypothesis 2: Lake stratification and oxygen depletion in the hypolimnion create conditions favorable for mobilization of phosphorus from benthic sediments. Physical and chemical conditions during the growing season at the sediment-water interface are capable of mobilizing phosphorus from the sediments.

Data Needed to Address Hypothesis: A spatial and vertical array of in-lake water-quality measures (physical, chemical, and biological) related to algal growth and metabolism in the epilimnion and nutrient concentrations at the sediment-water interface.

Reservoir Hypothesis 3: The bioavailable phosphorus stored in sediments in West Thompson Lake is large relative to the current annual incoming load from the Quinebaug River.

Data Needed to Address Hypothesis: Sediment volume, sediment phosphorus content, and the soluble phosphorus fraction of sediment phosphorus.

Reservoir Hypothesis 4: Phosphorus in treated effluent from municipal wastewater-treatment facilities upstream from West Thompson Lake is a major source of the phosphorus stored in sediments in West Thompson Lake. Sufficient phosphorus is retained during the winter months to create a large sediment source of nutrients.

Data Needed to Address Hypothesis: Quantification of annual and seasonal phosphorus loads from wastewater-treatment facilities; an estimate of the magnitude of this source relative to other sources for West Thompson Lake; an estimate of the seasonal retention of nutrients.

Freshwater Streams

Accurately determining the overall processing and transport of nutrient loads, particularly on a seasonal basis, would provide a framework for water-resource managers to use in understanding and managing nutrient-related problems in the Quinebaug River Basin. Information derived from studies of nutrient-cycling processes in impoundments would also support understanding of occurrence and transport in streams. Process-oriented information includes time-of-travel information and the role of streamflow regulation in determining water quality.

Spatial gaps in the water-quality monitoring network may relate to large unmonitored drainage areas, long river reaches with poorly understood processes, or local areas with specific nutrient sources that are important in terms of understanding water quality. Some monitoring gaps in the Thames Basin include:

- the Quinebaug River immediately upstream and downstream from West Thompson Lake;
- the central reach of the Quinebaug River from Pomfret Landing to Jewett City;
- small, relatively homogeneous subbasins with no point sources.

Other specific locations may be identified in the process of evaluating results from current studies in the Quinebaug River Basin, or through an evaluation of monitoring needs for the entire Thames River Basin.

River Hypothesis 1: Phosphorus loads and organic detritus exiting from West Thompson Lake (or other impoundments) create conditions favorable for the development of algal blooms in downstream reaches of the Quinebaug River.

Data Needed to Address Hypothesis: Nutrient budget and related information from current study in West Thompson Lake; seasonal nutrient concentrations and loads at reservoir outlet; quantity and composition of organic load from West Thompson Lake.

River Hypothesis 2: Effluent from wastewater-treatment facilities in Massachusetts and Connecticut is the major source of nutrient loads on the main stem of the Quinebaug River.

Data Needed to Address Hypothesis: Accurate seasonal point-source load data; quantification or estimates of nutrient loads from various nonpoint sources.

River Hypothesis 3: In some subbasins of the Quinebaug River, nonpoint sources, including agricultural sources, are major sources of stream nutrient loads.

Data Needed to Address Hypothesis: Quantification of nonpoint nutrient sources and loads.

River Hypothesis 4: Tributaries with largely forested drainage areas currently provide a substantial factor of dilution to the main stems of the Quinebaug and Shetucket Rivers. Continued development in forested areas will lead to stream-quality impairments that will eventually have an impact on larger streams.

Data Needed to Address Hypothesis: Nutrient concentration data and load estimates for the relatively pristine watersheds in the Thames River Basin. Estimates of how these concentrations and loads may change at different levels of development.

River Hypothesis 5: Seasonal low streamflows and streamflow regulation contribute to conditions that promote seasonal algal blooms.

Data Needed to Address Hypothesis: Integrated stream-discharge information for key locations in the Quinebaug River Basin; time-of-travel studies for different levels of streamflow; information on how the magnitude and duration of regulation affects low streamflows.

River Hypothesis 6: A combination of factors, including sunlight, water temperature, low stream discharge, backwater conditions, and nutrient concentrations, creates the necessary biogeochemical conditions for the development of algal blooms on the Quinebaug River. A study of nutrients in the Quinebaug River (Colombo and others, 2004) has linked algal blooms to elevated nutrient concentrations. However, the actual trigger, or combination of factors, for the development of algal blooms is not known.

Data Needed to Address Hypothesis: Detailed seasonal data on nutrient concentrations and loads, and the composition and dynamics of algal populations; time-of-travel information; and effects of streamflow regulation.

Norwich Harbor and the Thames River Estuary

The scientific community has to answer two key questions for each estuarine ecosystem: (1) How does the "filter" work? (see p. 14–15 for an explanation of "filter") and (2) What kinds of tools can we develop and use to help guide management decisions about coastal enrichment? Available science-based tools for studying estuarine ecosystems include complex numerical models as well as simpler interpretive approaches.

Complex numerical models representing estuarine hydrodynamics and water-quality conditions are sometimes used as a predictive tool, but this use may overextend the model's capabilities. A more appropriate use of modeling is as a way to understand how the system works, and for this it is necessary to have actual data measurements, strategically planned (J.E. Cloern, U.S. Geological Survey, oral commun., 2003). The particular physical problem represented by Norwich Harbor and the Thames River Estuary has been described as an "extreme test" for any numerical model (J.E. Cloern, U.S. Geological Survey, oral commun., 2003). Previous models applied to this ecosystem have not been fully successful (Connecticut Department of Environmental Protection, 2002c).

The complexity of the harbor-estuary system, and the experience with previous models, suggest that the necessary steps for understanding Norwich Harbor and the Thames River Estuary are:

- evaluation and interpretation of existing data,
- identification of critical data needs,
- implementation of strategic monitoring to fulfill identified needs, and
- synthesis and interpretation of existing and new data.

Such a program of monitoring and interpretation could provide an understanding of the system that would be important to the successful design of future modeling efforts.

The two principal questions for Norwich Harbor and the Thames River Estuary are: (1) What are the circulation patterns in the harbor and estuary; and (2) What are the quantities of organic matter contributed by different sources? The inputs of organic matter include the nutrient loads, and the circulation patterns constitute a major part of the local "filter" that determines ecosystem responses. Participants in the Thames Symposium (Connecticut Department of Environmental Protection, 2002c) discussed hydrodynamic factors and sources of organic material that may collectively lead to low dissolved oxygen conditions in Norwich Harbor and the upper Thames River Estuary, but did not reach a consensus on the relative importance and contribution of the various factors. This circumstance itself points to the need for additional monitoring to define the physical conditions of estuarine circulation and to quantify the sources, transport, cycling, and production of nutrients and organic material. Definition of circulation patterns in the harbor and upper estuary requires data collection over a range of freshwater inflow conditions and through full tidal cycles.

Acquisition and interpretation of a dataset that represents the physical, chemical, and biological conditions of the harbor, in three dimensions and over time periods that represent seasonal and interannual variations in these conditions, would be a necessary prerequisite to developing a conceptual model of estuarine processes and to any future modeling effort.

An investigation of the loads of nutrients and organic material delivered to the harbor by freshwater streams would be an important complement to more complex harbor and estuary studies, and may need to precede such studies. Definition of seasonal freshwater loads would be an important part of this effort. Fulfillment of this objective would depend in part on evaluation and synthesis of information for the freshwater drainage basin upstream from the harbor, and may require discharge and water-quality monitoring for load estimation at additional locations. Quantification of nutrient sources could also include process-specific research in the harbor itself. Such research can be expensive, but the potential for acquiring important information is high. Information on water-quality conditions and algal productivity, in three dimensions and over a range of streamflow and tidal conditions, would be necessary, as would be information on sediment mass and composition, and nutrient fluxes from the sediment.

Estuary Hypothesis 1: Circulation patterns, which vary hourly, daily, seasonally, and annually in response to freshwater inflows and tides, determine the ecosystem response to nutrients and organic material.

Data Needed to Address Hypothesis: Spatially and vertically distributed hydrodynamic data collected over a range of streamflow and tidal conditions for Norwich Harbor and the upper Thames River Estuary.

Estuary Hypothesis 2: Algal productivity in the harbor itself is an important source of the organic material that settles, decomposes, and causes hypoxia.

Data Needed to Address Hypothesis: Spatially and vertically distributed water-quality monitoring in Norwich Harbor during one or more growing seasons, including physical properties, chemical constituents, nutrients, biological measures, light penetration, and algal community composition; solute residence time in upper and lower layers of the water column.

Estuary Hypothesis 3: Nutrients and organic material delivered to Norwich Harbor by freshwater streams contribute to hypoxia by fueling algal blooms that deplete oxygen during decomposition.

Data Needed to Address Hypothesis: Quantification of nutrient and organic loads from freshwater tributaries; annual and seasonal variability in loads. Other monitoring locations in addition to present long-term stations may be necessary for a complete picture of nutrient and organic loads.

Estuary Hypothesis 4: Sediment in the harbor is the major source of oxygen demand.

Data Needed to Address Hypothesis: Sediment distribution, thickness, and composition; measures of sediment oxygen demand; seasonal variability in water quality at the sediment-water interface that affects organic decomposition and mobilization of nutrients.

Summary of Suggested Investigations to Fulfill Information Needs

Acquisition of fundamental information is important for understanding and managing complex ecosystems. Information needs in the Thames River Basin can be thought of as taking place along a continuum of monitoring, interpretation, and modeling, with modeling seen as a tool that enables higher-level interpretations. Monitoring data provide the basis for interpretations ranging from the simple to the complex. Interpretive studies provide insights into the system and provide a basis for determining the kinds of modeling approaches that will be most useful. Information needs become increasingly demanding in complex modeling approaches. *The continuum of monitoring, interpretation, and modeling is also a cyclic process in which interpretive studies may identify additional data requirements that have to be filled before more complex studies can be undertaken* (fig. 10). Modeling approaches also range from the simple to the complex, with the simpler approaches seen as building blocks for more comprehensive approaches requiring multiple data sets and a comprehensive understanding of the system to be modeled.

This summary of suggested investigations emphasizes the need to proceed from the simple to the complex, and to identify and acquire fundamental information that would support future, more complex and comprehensive studies. Suggested investigations are presented in a progressive sequence, so that the initial studies would provide necessary information for the more complex studies that may take place later in time. At each successive level of investigation, study designs would depend on results and questions generated at previous levels. At least initially, the studies may be divided between the freshwater and estuarine parts of the river basin. As fundamental information needs are identified and met, and processes are understood for the separate freshwater and estuarine systems, then studies could be undertaken to link the two systems.

The progressive sequencing of suggested investigations is expected to complement the adaptive implementation approach to the TMDL process that has been adopted by CTDEP. The CTDEP can use existing information for the Thames Basin, while also conducting a carefully designed program of monitoring, interpretation, and modeling to obtain information important to the long-term understanding, management, and improvement of water quality in the Thames River Basin (Connecticut Department of Environmental Protection, 2002c). Management plans will be responsive to new information and interpretations as they become available.

Although the investigations suggested in this Science Plan have been defined based on geography, hydrology, ecosystem processes, and general information needs, these are not intended as rigid divisions of the suggested work. In practice, CTDEP may choose to divide, recombine, or add work elements in various ways to meet agency needs and priorities within available resources. The scope of many of these suggested investigations can be defined using a tiered approach to meet immediate, high-priority information needs; the scope can be expanded later to address the needs of more comprehensive investigations.

Conceptually, and ideally, synthesis and interpretation of available data on a watershed scale would precede new investigations. As a practical matter, however, it is likely that analysis, synthesis, and interpretation of available data would be conducted on a more limited geographic scale as part of numerous investigations within the watershed.

As water-resource managers evaluate actions necessary to support water-quality restoration and protection, the temporal sequence of scientific investigations and management actions (fig. 13) would need to be related to the geographic distribution of water-quality impairments and information needs (fig. 14). A flowchart showing a generalized time line for a suggested geographic sequence of scientific investigations and nutrient TMDL development is shown in figure 13. The geographic units in the time line are color-coded to subbasin areas shown on the map of the Thames River Basin in figure 14. The time line shows a geographic sequence of investigations that could take place over the short-term (1-3 years), medium-term (4-7 years), and long-term (8-12 years). Scientific investigations for some water bodies or drainage areas with complex problems, including the Quinebaug River Basin and Norwich Harbor, may include short-term, medium-term, and long-term studies. The indicated time periods are generalized rather than definitive; new findings from completed investigations (as well as other factors) may alter the direction, scope, and duration of future studies.

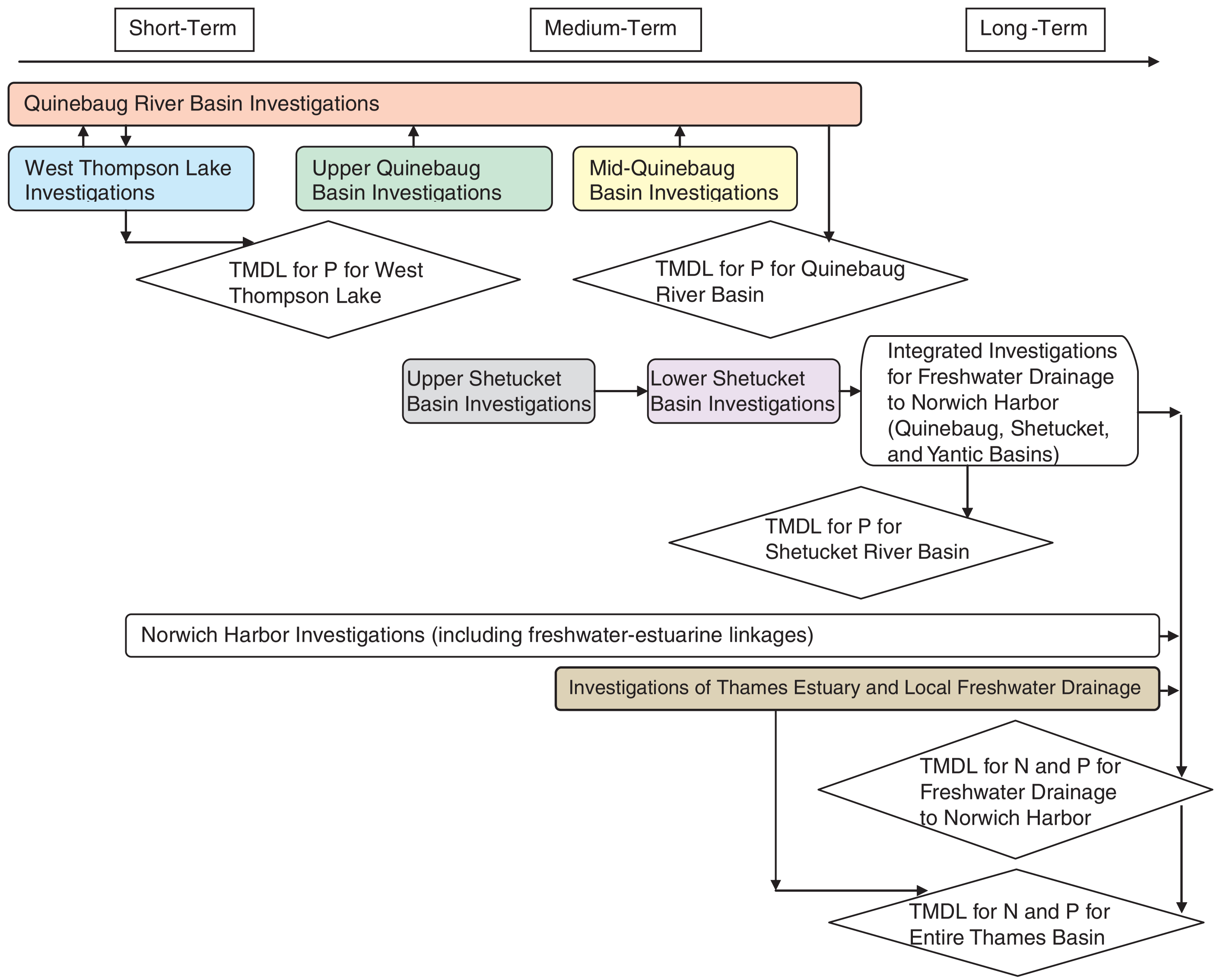

Figure 13. Generalized time line for geographic sequence of scientific investigations and nutrient TMDL development. Geographic units are color-coded to the drainage areas shown in figure 14.

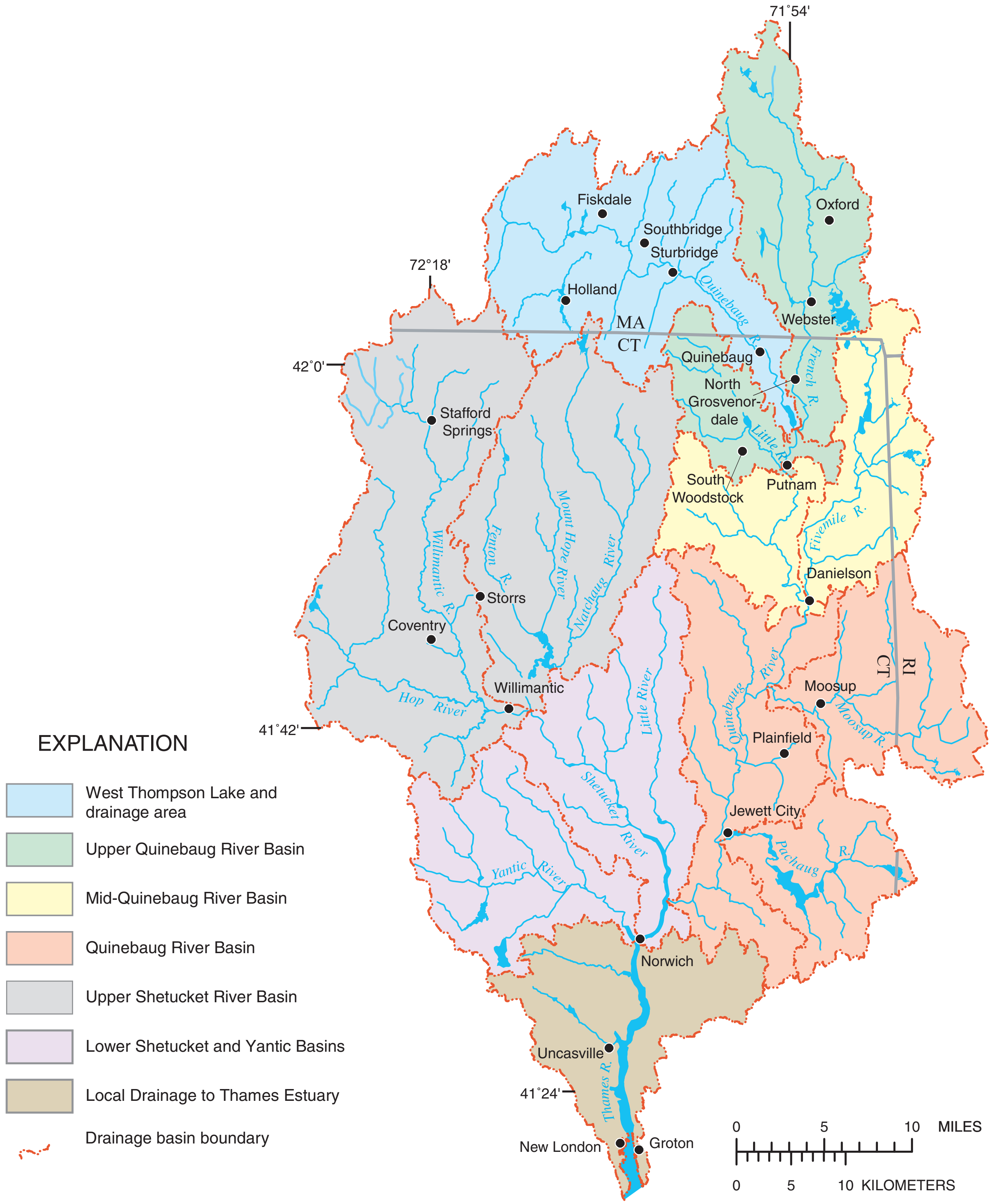

Figure 14. Map of the Thames River Basin showing the geographic units for the sequence of nutrient-related hydrologic investigations suggested to support water-quality improvements in the basin. Successive downstream drainage areas are color-coded as separate geographic units as a graphical convenience. However, suggested investigations may encompass drainage areas that include upstream areas shown on this map as separately defined units. Geographic units in this map are color-coded to correspond to the geographically based sequence of scientific investigations diagrammed in the generalized timeline in figure 13.

The conceptual model for the Thames River Basin indicates that, particularly in the Quinebaug River Basin, nutrient-related water-quality problems in upstream reaches of the basin influence, cause, or exacerbate similar problems in downstream reaches of the basin. Consequently, the drainage basins of the Shetucket and Quinebaug Rivers have been subdivided into smaller drainage areas (fig. 14), and the temporal sequence of suggested investigations follows a geographic sequence from upstream to downstream (fig. 13). The time line is also based on the presence and severity of impairments, with Quinebaug Basin investigations preceding Shetucket Basin investigations. Successive downstream drainage areas are color-coded as separate geographic units as a graphical convenience in figure 14. However, some suggested investigations may encompass larger drainage areas, including upstream areas shown in figure 14 as separately defined units.

The suggested geographic sequence in figure 14 is based on natural hydrologic units, existing or suggested monitoring locations, locations of major point sources, or locations of major tributary streams. The geographic groupings could be modified as additional scientific information is gathered and management actions are implemented. Most or all of the freshwater information needs identified in figure 11 would need to be addressed for each successive downstream portion of the Thames River Basin.

The suggested scientific investigations are listed below in two categories: Freshwater Investigations and Estuarine Investigations. Most of the investigations listed are suggested as new studies. Ongoing and recently proposed studies in the Thames River Basin are also included to provide a complete picture of scientific work envisioned for the watershed. For ease of reference between the text discussion and related illustrations, the investigations described below have been labeled and numbered based on their category: Freshwater (F1, F2, etc.), or Estuarine (E1, E2, etc.).

The long-term success of investigations designed to support management of nutrient-related water-quality problems depends on continued discussion, cooperation, and information sharing among the many agencies and organizations with interests in improving water quality in the Thames River Basin. Periodic meetings of interested groups would facilitate information sharing and provide helpful guidance to the design of investigations. Many suggested investigations offer opportunities for interdisciplinary work and partnerships.

The value of future investigations in the Thames River Basin would be increased by making a library of information available to researchers and investigators. Such a library could include published reports; reports, data, and other information in various electronic formats; and less formal agency reports that are available for public use. Sources of information could include state and federal agencies, academic institutions and organizations, private sector institutions, and private nonprofit organizations. Contact information or library locations for agencies and organizations could be included to facilitate locating materials. Designation of a central repository could be considered for documents that are not widely available.

Suggested Freshwater Investigations

Specific hydrologic investigations can be designed to address the hypotheses formulated in the Assessment section of this report, and to support the general information categories shown in figure 11. Some investigations would provide information that supports more than one of these categories. As an example, a flowchart presents a suggested suite of investigations for West Thompson Lake and its drainage area (fig. 15). Numbered investigations listed in the boxes on the left-hand side of figure 15 are described below. The suggested investigations support the scientific information categories for freshwater (figs. 11 and 15). A similar flowchart could be designed for a drainage basin or subbasin, or for the drainage area to a particular river reach. Many of the investigations shown in the West Thompson Lake example also would supply information needed for the Quinebaug River; the scope of these investigations could be designed for larger or smaller drainage areas, or in a downstream sequence, depending on needs identified by water-resource managers.

Visualization of suggested investigations in relation to hydrologic and biogeochemical processes also is useful. As an example, a map and generalized cross sections of West Thompson Lake show numbered investigations noted at locations in the system where the suggested investigations could provide information on nutrient loads to and from the lake, as well as cycling processes within the lake (fig. 16).

Although many of the suggested freshwater investigations are focused primarily on phosphorus, it would be important to incorporate nitrogen, and in some cases organic carbon, in these studies to understand sources, cycling, and transport of these constituents, and to provide information that would support understanding of nutrient and organic loads to the Thames River Estuary.

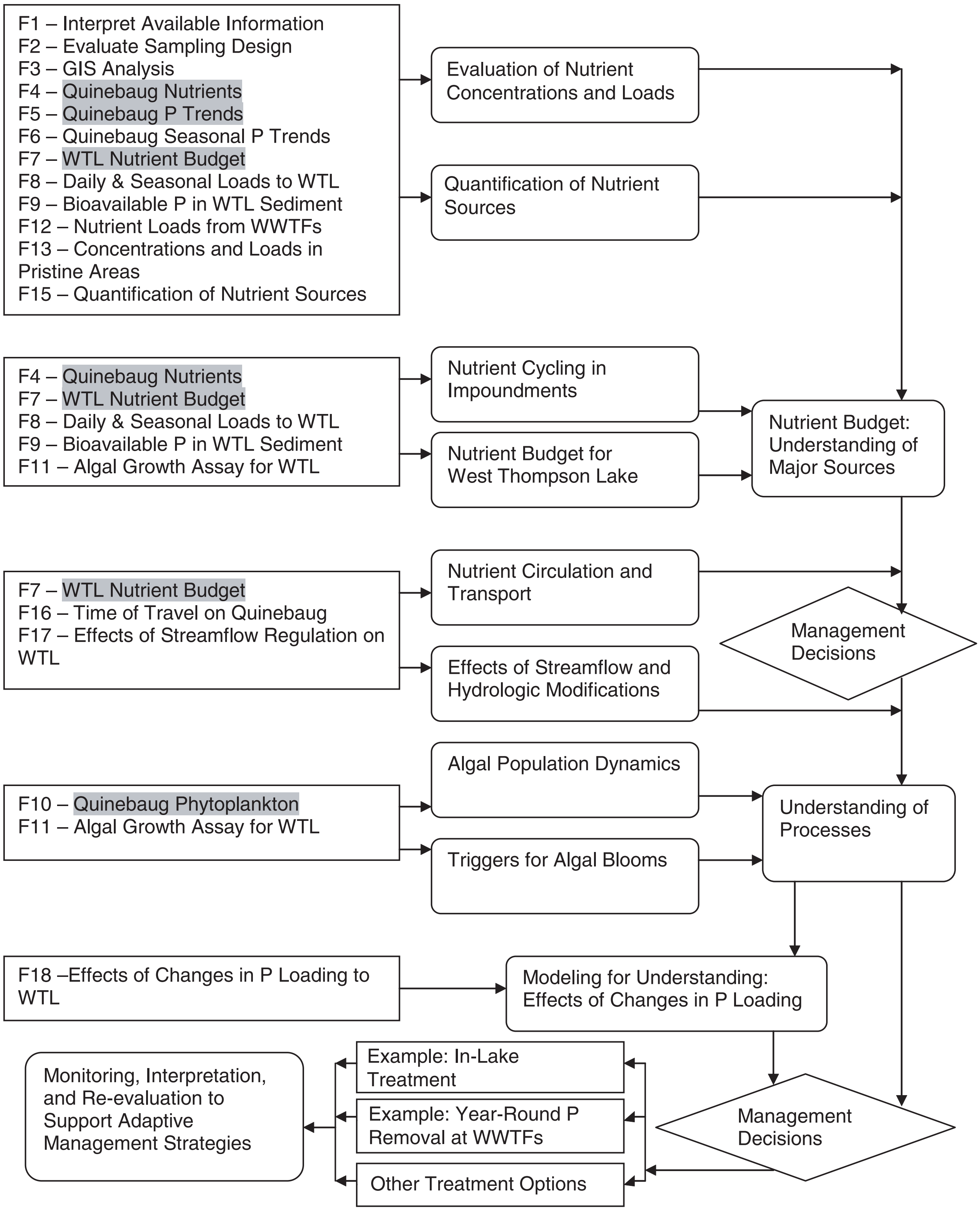

Figure 15. Sequence of suggested investigations to support information needs for nutrient TMDL development for West Thompson Lake and its drainage area. Highlighted investigations are in progress or are completed.

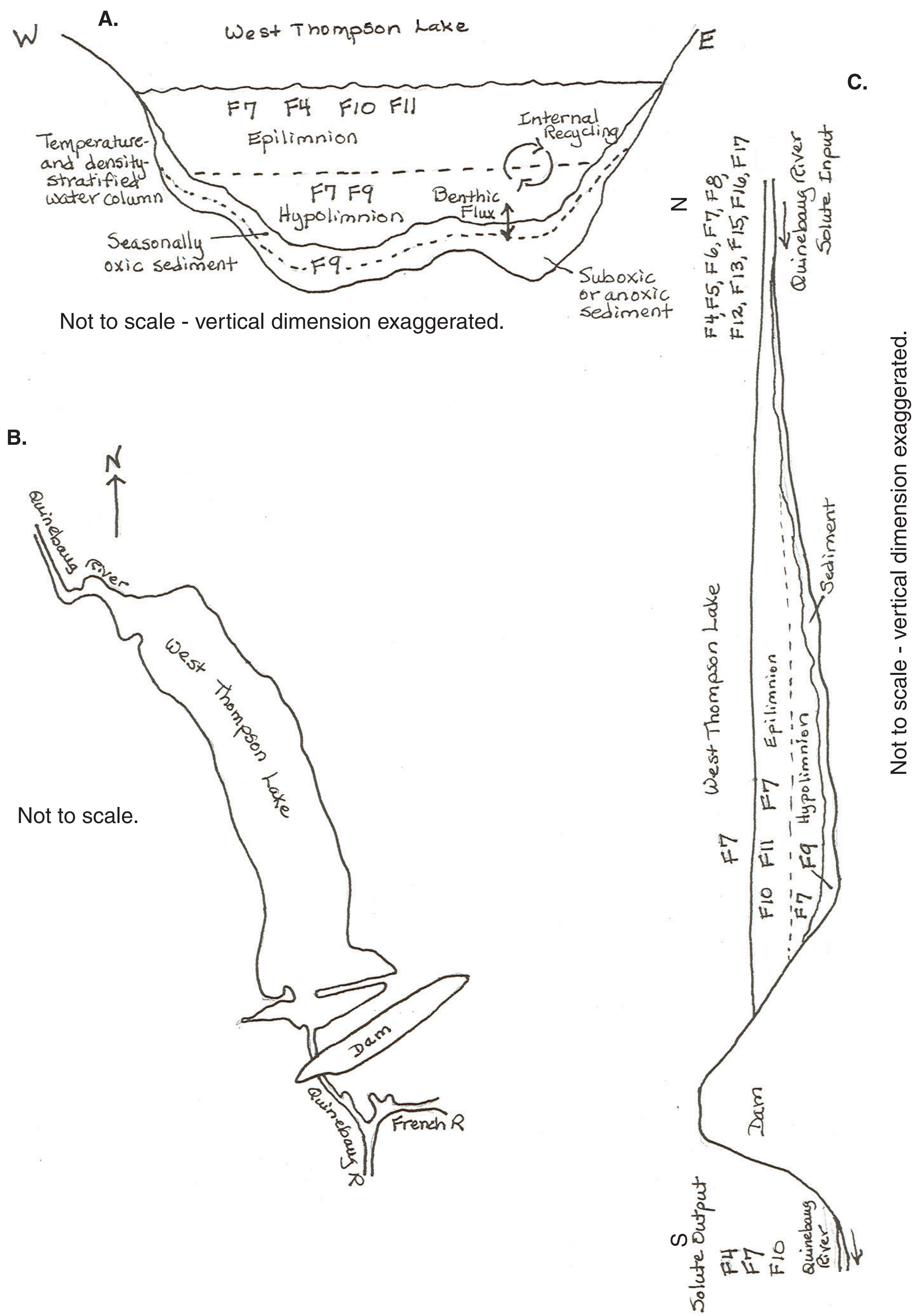

Figure 16. Generalized diagrams of West Thompson Lake showing relation of suggested investigations to hydrologic and biogeochemical processes: A. Generalized W-E cross section; B. Map of West Thompson Lake, northeastern Connecticut; C. Generalized N-S cross section. Location of West Thompson Lake shown in figure 6. For an explanation of numbered codes for scientific investigations, refer to text and figure 15. Metalimnion not shown in generalized cross sections. Generalized conceptual model for solute transport modified from J.S. Kuwabara (U.S. Geological Survey, written commun., 2004).

F1 – Analysis and Interpretation of Information on Nutrient Sources and Water Quality in the Thames River Basin, 1970-2004

A holistic synthesis of information on nutrient sources and water quality would support the work of numerous managers and scientists involved in nutrient-related problems and investigations in the watershed. As noted by Puckett and Triska (1996) in a broader national context, a wealth of information from monitoring and assessment studies has been underutilized from a system perspective. The Thames Science Plan has identified a number of studies by CTDEP, USGS, and other agencies and programs where a coordinated interpretation of existing data could yield valuable insights and a more comprehensive picture of water-quality conditions and processes. This project would also contribute information to the Evaluation of Surface-Water Quality Sampling Design for the Thames Basin (F2). The project on Spatial (GIS) Analysis of Thames River Basin Information (F3) would contribute substantially to the effectiveness of the suggested information synthesis.

F2 – Evaluation of Surface-Water-Quality Sampling Design for the Thames River Basin

A monitoring plan could identify the specific locations that would provide the best information for multiple purposes. The Thames Symposium (Connecticut Department of Environmental Protection, 2002c) recommends a potentially extensive monitoring program as a high priority. The monitoring would be designed to serve a variety of assessment, interpretive, and modeling purposes. General types of locations to be included have been listed as part of the Symposium recommendation. Likewise, the Thames Science Plan project has identified several forms of monitoring needs, in terms of geographic and temporal distribution, as well as specialized studies of specific systems or processes. *This project would build on the conclusions of the Thames Symposium, the Thames Science Plan, and additional analyses to identify specific monitoring locations to fulfill short-term and long-term monitoring needs.* The project could be conducted in close conjunction with two related projects: Analysis and Interpretation of Information on Nutrient Sources and Water Quality in the Thames River Basin (F1), and Spatial (GIS) Analysis of Thames River Basin Information (F3).

The Evaluation of Surface-Water-Quality Sampling Design could be an ongoing or periodically revisited project, because, as management strategies are implemented, carefully designed monitoring plans also would need to be implemented to evaluate the results of these programs. Estimates of the length of time that is likely to be required to see an effect from an implementation program would be necessary, in order to estimate the time frame for related monitoring.

F3 – Spatial (GIS) Analysis of Thames River Basin Information

Spatially referenced information, summarized and interpreted, would support many aspects of the suggested scientific investigations in the Thames River Basin. A spatial analysis of information, including natural drainage basin characteristics, land use, streamflow characteristics, and other features, would contribute fundamental information to essentially all of the ongoing and suggested projects related to water-quality management and improvement in the Thames Basin.

This analysis could also examine ways that land (drainage) areas and stream reaches could be categorized for future modeling efforts, such as the extrapolation of nutrient concentrations and loads to unmonitored areas, or the development of time-of-travel information based on drainage-basin characteristics.

F4 – Nutrient Concentrations and Loads in the Quinebaug River Basin

Information on the spatial and temporal distribution of nutrient concentrations and loads is essential for evaluating nutrient sources and developing nutrient-related TMDLs. This ongoing (2004) study has augmented information on the spatial and temporal distribution of nutrient concentrations in the Quinebaug River Basin through a monitoring program from October 1999 to September 2001 that included: increased monitoring frequency at long-term cooperative monitoring locations, monitoring at additional temporary main stem and tributary locations, and monitoring at four wastewater-treatment facility discharges. Nutrient load analyses developed as part of this project are expected to provide information on the spatial and temporal distribution of major nutrient sources. Information on the occurrence, distribution, and types of algae in the Quinebaug River, collected as part of this study, has been incorporated and presented in the study described in investigation F-10, Nutrient Enrichment and Algal Productivity in the Quinebaug River Basin.

F5 – Quinebaug Phosphorus Trends

Management of nutrient-related water-quality problems requires periodic assessment of trends in nutrient concentrations. The report resulting from this study (Trench, 2004) presents an analysis of trends in total phosphorus concentrations, and an evaluation of sampling schedules for monitoring future trends in phosphorus, for two stations on the Quinebaug River for selected periods of record during 1971-2001. Although long-term decreases in total phosphorus concentrations have taken place in the Quinebaug River, recent concentration increases were detected at both stations. This report was completed as part of the larger Thames Science Plan project.

F6 – Seasonal Phosphorus Trends in the Quinebaug River

Important nutrient sources and processes in the Quinebaug River Basin are seasonally variable. ***An analysis of seasonal trends in total phosphorus concentrations could help to define the relative importance of these sources and processes by identifying the seasons in which trends originate.*** Trend studies conducted in Connecticut to date have evaluated long-term annual trends; that is, detected trends may originate in any season of the year.

F7 – Annual Nutrient Budget for West Thompson Lake

Development of a nutrient budget for West Thompson Lake would support understanding of the possible seasonal transition of the lake from phosphorus sink to phosphorus source, and would provide information on the potential effects of the lake's outflow on downstream reaches of the Quinebaug River. A cooperative USGS-CTDEP study is currently (2005) underway to investigate phosphorus storage and seasonal cycling in West Thompson Lake, in the upper Quinebaug watershed. An estimate of the mass of phosphorus in sediments is an expected outcome from this project. A preliminary budget for nitrogen also is an expected outcome. Annual data are needed for understanding the possible seasonal transition of the reservoir from phosphorus sink to phosphorus source, and for developing an annual nutrient budget for the impoundment. Sampling for soluble reactive phosphorus at different levels in the water column during anoxic events is suggested to refine understanding of nutrient sources and cycling within the reservoir. Additional water-quality profiling data coupled with bathymetry information may be necessary to estimate the potential sediment source area for phosphorus under different areal extents of the anoxic zone in lake bottom waters.

Investigations to develop annual nutrient budgets for other lakes in the Quinebaug River Basin may be needed, based on results from the West Thompson Lake study and other suggested investigations.

F8 – Daily and Seasonal Nutrient Loads at West Thompson Lake

Nutrient TMDL development for West Thompson Lake would require annual and seasonal nutrient budgets that accurately describe all major sources of nutrients to the lake, including inflow from the Quinebaug River. Current nutrient-load estimates for the Quinebaug River are based on equations that relate constituent concentrations to mean daily flows. Regulation on the Quinebaug River can cause large hourly fluctuations in streamflow. ***Information on how nutrient concentrations vary with short-term streamflow variations can be used to determine whether standard load-estimation techniques provide an accurate estimate of stream nutrient loads delivered to West Thompson Lake.*** Information from continuous monitoring over a range of streamflow conditions would improve or validate estimates of nutrient loads from the Quinebaug River. Automatic samplers could be used to collect samples every 2 hours during selected 2-day periods representing low-, median-, and high-flow conditions.

F9 – Bioavailable Phosphorus in West Thompson Lake Sediment

Data from the West Thompson Lake study (F7), which have not been fully analyzed and interpreted, are expected to document an internal load of phosphorus and provide a crude mass balance of phosphorus in sediment. Total phosphorus measurements overestimate the amount of sediment phosphorus that is potentially mobile during anoxic events. ***Chemical fractionation of phosphorus would identify the amount of phosphorus that could be released to an anoxic water column.*** This analysis would complement the suggested measurement of soluble reactive phosphorus at different depths in the water column during anoxic events. Additional parameters related to algal blooms, including light and temperature, would be included in the depth profiles.

F10 –Nutrient Enrichment and Algal Productivity in the Quinebaug River Basin

Management actions to minimize or prevent nuisance algal blooms in the Quinebaug River Basin would require an understanding of where, when, and how elevated nutrient concentrations affect the rate of primary productivity. As part of the larger Thames Science Plan project, the CTDEP and the USGS initiated a study in 2002 to characterize the relation between nutrient enrichment and excessive algal productivity in the Quinebaug River Basin. The report produced by this study (Colombo and others, 2004) relates the location and timing of elevated nutrient concentrations to the occurrence of elevated seston chlorophyll *a* concentrations and pronounced increases in seston algal populations during the summers of 2000 and 2001. The report also provides estimated rates of primary productivity and respiration of seston algal communities. Information on the occurrence, distribution, and types of algae in the Quinebaug River, collected as part of investigation F4, Nutrient Concentrations and Loads in the Quinebaug River Basin, has been incorporated and presented in Colombo and others (2004).

F11 – Algal Growth Bioassay for West Thompson Lake

The emphasis in West Thompson Lake studies and suggested investigations has been on phosphorus. ***The trigger for algal growth, however, could be a shift in the ratio of dissolved inorganic nitrogen to dissolved inorganic phosphorus, rather than the concentration of a single nutrient, especially if the algal bloom is dominated by cyanophytes. Shifts in total phosphorus and total nitrogen may also indicate when most of the nutrient load has shifted from the dissolved form to particulates (algal cells in transport).*** The objectives of this suggested project are to (1) measure ratios of nitrogen to phosphorus (both total and dissolved forms) in the water of West Thompson Lake as well as upstream and downstream from the lake, and relate this information to algal growth and types of algae; (2) calculate shifts in total phosphorus and total nitrogen to evaluate algal transport out of West Thompson Lake; and (3) verify that phosphorus is the limiting nutrient in the lake using algal growth potential assays.

F12 –Annual and Seasonal Nutrient Loads from Wastewater-Treatment Facilities

In statewide studies that have estimated annual nutrient loads, findings typically indicate substantially larger loads during winter and early spring (high-flow months) than during summer and early fall (low-flow months) (Trench, 2000; Mullaney and others, 2002). The confidence interval on load estimates for winter months is also often larger than for summer months. ***Multiple lines of evidence suggest that it is important to understand the sources of nutrient loads transported by streams during winter and early spring. Currently, municipal wastewater-treatment plants in the Massachusetts part of the Quinebaug watershed require phosphorus removal on a seasonal basis, generally from April to October. An investigation to quantify seasonal nutrient loads in general, and specifically seasonal nutrient loads from treatment plants, would be a necessary component of determining the sources of nutrients in the Quinebaug River Basin.*** Synoptic sampling at stream locations and at wastewater-treatment facilities is suggested to supplement available data on nutrient loads from wastewater-treatment facilities. Information on seasonal phosphorus loads in the upper Quinebaug watershed will support development of annual and seasonal phosphorus budgets for West Thompson Lake. For TMDL development, source loading estimates, as well as information on the seasonal timing of the sources, would be needed. Although phosphorus is the nutrient of interest for West Thompson Lake, information on nitrogen loads would be necessary for understanding the larger framework of freshwater transport of nitrogen to the Thames River Estuary.

F13 –Nutrient Concentrations and Loads in Pristine, Forested Areas

Clean streamflow from relatively pristine forested areas provides an important measure of dilution for impaired stream reaches, but the high quality of streams draining these areas is not permanent, and may not be protected. Sampling for nutrients and related constituents in pristine areas would be necessary to develop a baseline of information, especially in areas that are under significant development pressure. This suggested project would use agency monitoring programs (such as the CTDEP Ambient Biological Monitoring Program and the USGS-CTDEP water-quality monitoring program) to provide coordination and direction for the citizen monitoring programs of watershed organizations and other public-service groups, resulting in more effective use of resources and more usable data. Using long-term monitoring stations or synoptic monitoring events, the project would develop correlations between field parameters measured in citizen monitoring programs and field- or laboratory-analyzed constituents measured in agency programs. The CTDEP Rapid Bioassessment Survey is an existing program that is a potential partner for this effort. Citizen monitoring projects have the potential to extend the reach of agency programs, and GIS analysis of subbasins would enable extrapolation of monitoring data to unmonitored areas. Taken a step further, analysis and correlation of information from forested subbasins undergoing development may lead to an understanding of early indicators of water-quality deterioration. The geographic distribution of forested subbasins to be included in this analysis would be determined by GIS analysis of subbasin information (F3) and a set of criteria to be developed for this project.

F14 – Assessment of the Contribution of Nutrients from Ground-Water Inflow

Nutrient studies in other areas of Connecticut have shown that ground water can contribute a substantial percentage of the nitrogen load in streams in urban and agricultural areas (Mullaney and Grady, 1997). ***A full understanding of the relative importance of different sources of nutrients in the Thames River Basin would include estimation of the nutrient load transported by ground water.*** These estimates may be based in part on information from similar areas in other parts of Connecticut, combined with specific land-use information for subbasins of the Thames Basin (F3). Accurate estimates will also require some combination of low-flow sampling, hyporheic zone sampling, and ground-water sampling in selected reaches of interest.

F15 – Quantification of Point and Nonpoint Sources of Nutrients in the Quinebaug River Basin

A synthesis of information on point and nonpoint nutrient sources for the Quinebaug River Basin would be necessary following completion of other investigations to document specific nutrient sources. Information on point and nonpoint sources of nutrients is or would be available from several ongoing or suggested investigations (F4, F7, F8, F12, F13, F14). Some information, however, is lacking, as is a synthesis of available information. The Eastern Connecticut Conservation District has proposed a study to evaluate agricultural nutrient sources, and is a potential partner for this project. Results from the Quinebaug nutrients study may be used to identify locations or reaches where there are major increases in stream nutrient loads, and this information could be used in selecting additional monitoring locations to define nutrient loads and their sources.

F16 – Time-of-Travel Studies on the Quinebaug River

Time-of-travel information was identified during the Thames Technical Workshop (April 2003) as a key piece of information for understanding and interpreting nutrient transport and eutrophication in the Thames River Basin. A key area for time-of-travel work in the Thames Basin is in the Quinebaug River Basin, although work in other subbasins of the Thames may eventually be necessary for a full understanding of the system and development of a basinwide TMDL. Time-of-travel information is valuable for a number of potential applications, and is an important building block for water-quality modeling. This information would also constitute a first step in understanding how flow regulation affects water-quality conditions in the Quinebaug River Basin. Information on time-of-travel could help to determine where nutrients are processed, and could assist in understanding the sources, transport, and fate of nutrients.

CTDEP has conducted time-of-travel studies in some streams in Connecticut, and this investigation would build on that information. Time-of-travel through the impoundments along the Quinebaug is not known. This project proposes to undertake a series of time-of-travel studies on the Quinebaug River, at two or three different flow conditions. Low-flow conditions may be most important for understanding effects on the freshwater system, and high-flow conditions may be most important for the estuary. The project could take advantage of available expertise and equipment in the CTDEP and other agencies. Techniques for time-of-travel studies are well-established and are generally considered to be cost-effective, in terms of the amount of information gained for project expenditures. Several agencies, including municipalities, may benefit from the results of such a study and are potential partners.

The USGS has developed a method for predicting travel time and longitudinal dispersion in streams based on drainage basin and stream characteristics (Jobson, 1996). The potential exists for a more comprehensive investigation of travel time in the Thames River Basin. Results from time-of-travel studies on selected stream reaches could be used to modify predictive equations, and this information, coupled with information on drainage basin characteristics generated by GIS analysis (F3) could be used to generate time-of-travel information for numerous streams in the watershed.

F17 – Streamflow Regulation and Effects on West Thompson Lake

Low streamflow conditions and regulation on the Quinebaug River are thought to create conditions favorable for the development of seasonal algal blooms in West Thompson Lake. This suggested investigation would document low streamflow conditions and regulation episodes, and relate the timing of these conditions to the growth and development of algal blooms in West Thompson Lake. Time-of-travel information (F16) for the upper Quinebaug River Basin would provide supporting information for this investigation.

F18 – The Effects of Changes in Phosphorus Loading to West Thompson Lake

If a phosphorus budget is developed for West Thompson Lake, a simple model is suggested to evaluate the effects of changes in phosphorus loading on chlorophyll concentrations in the reservoir. Studies by the USGS in Wisconsin have investigated phosphorus in lakes and lake sediments and could provide guidance in designing this suggested investigation (Robertson and Lenz, 2002; Robertson and others, 2005).

F19 – Spatial and Temporal Distribution of Nutrient Enrichment and Phytoplankton Algal Growth in the Quinebaug River Basin

Understanding the seasonal development of algal blooms requires information from a sequence of key locations along river reaches and in impoundments, and a time series of data with a frequency sufficient to document related changes and developments in water quality and algal populations through the course of the growing season. Information from a study in the Quinebaug River Basin (F4, F10) has documented the relation between nutrient enrichment and phytoplankton algal growth for a limited number of times and locations. The ongoing study in West Thompson Lake (F7) will provide additional information on seasonal phosphorus sources. Information from current studies in the Quinebaug River Basin will provide guidance for selecting the key locations for monitoring. Strategically placed continuous monitoring fluorometers could provide extensive information on algal biomass over time. The suggested investigation is intended to provide a reasonably complete picture of the spatial and temporal distribution of algal dynamics and related water-quality conditions over at least one complete growing season.

F20 – Streamflow Regulation and Water Quality in the Quinebaug River

Low streamflow conditions in the Quinebaug River system have been linked, at a qualitative level, with seasonal algal blooms. This suggested investigation would examine the effects of low streamflow conditions, regulation, and impoundments on the growth and development of algal blooms. Time-of-travel information (F16) would be a key element for this investigation. Information from this study may be used to address the question of whether streamflow can be managed to improve water-quality conditions. A simple modeling approach may be suggested as part of the study.

F21 – Simulation of Phosphorus and Algal Dynamics on the Main Stem of the Quinebaug River

Several elements are necessary for simulation of phosphorus and algal dynamics in the Quinebaug River. Previous investigations were designed to provide additional stream discharge and water-quality data in unmonitored stream reaches; provide information on water quality and algal dynamics; quantify point sources in the drainage basin; evaluate the effects of seasonal phosphorus removal in wastewater-treatment facilities upstream from West Thompson Lake; quantify nonpoint sources, including ground-water inflow; evaluate the significance of West Thompson Lake and other impoundments as seasonal sources of phosphorus; and provide information on streamflow dynamics and constituent time-of-travel. Additional parameters, including phosphorus uptake rates, phytoplankton growth rates, and oxygen diffusion rates, would need to be measured specifically for the Quinebaug River to develop a meaningful model for the system. ***A one-dimensional model is suggested to use the complex suite of information developed in previous studies to describe the development of algal blooms and diel oxygen dynamics in the Quinebaug River.*** The investigation would address the questions: How do algal blooms develop? How do bloom dynamics relate to streamflow? How do algal blooms propagate downstream?

F22 – Nutrient Trends in the Thames River Basin

Instream nutrient concentrations are not static, and previously detected trends do not represent future conditions. ***Periodic assessment of trends in nutrient concentrations at key locations in the Thames River Basin would be an important component of understanding and managing nutrient-related water-quality problems, and assessing watershed responses to the implementation of management plans.***

F23 – Preliminary Quantification of Nutrient Sources and Loads for the Shetucket River Basin

Eutrophication is not currently a problem in the Shetucket River Basin. The system may be less sensitive to nutrient inputs because of natural conditions, or because of the lesser magnitude of the sources. Substantial point and nonpoint sources exist in the basin, however, and continued development may eventually stress the system. ***Evaluation and assessment of current conditions could identify monitoring needs, and could evaluate the potential for future nutrient-related water-quality problems.***

F24 – Simulation of Nutrient Loads Based on Watershed Characteristics

A holistic understanding of nutrient sources and transport is needed for the Thames River Basin. The USGS has developed a statistical method that relates instream water-quality measurements to spatially referenced watershed characteristics, such as contaminant sources and environmental factors that influence the terrestrial and stream transport of contaminants (Smith and others, 1997, p. 2782). The statistical method, referred to as SPARROW (Spatially Referenced Regressions On Watershed attributes), is designed to address problems posed by gaps in a monitoring network, sampling biases toward specific problems, and the heterogeneity of drainage basins (Smith and others, 1997, p. 2781-2782). Regression models based on this method have a number of potential applications related to estimating nutrient concentrations and loads, and evaluating the relative importance of nutrient loads from different basins and subbasins. ***Application of the SPARROW modeling technique to the Thames River Basin could aid in identifying specific subbasins and nutrient sources that are important contributors to nutrient enrichment in freshwater and estuarine areas. This information, in turn, could be used by water-resource managers to develop effective strategies for prioritizing research and regulatory efforts.***

F25 – Interstate Thames Watershed Model

A long-term goal of the investigations suggested in this Science Plan is to develop the streamflow, water-quality, and biological data and related interpretations necessary to understand nutrient-related problems in the Thames River Basin, and to integrate this information in an interstate watershed model that could be used to understand and manage the freshwater system holistically. Development of this model would be a long-term investigation that depends on acquisition of fundamental information for the various components of the freshwater system. The goal would be to develop a model at a finer scale than previous regional watershed models that included the Thames Basin.

Estuarine Investigations

Specific hydrologic investigations can be designed to address the hypotheses formulated in the Assessment section of this report, and to support the general information categories shown in figure 12. Some investigations would provide information that supports more than one of these categories. A flowchart presents a suggested suite of investigations for Norwich Harbor (fig. 17). Numbered investigations listed in the boxes on the left-hand side of figure 17 are described below. The suggested investigations would support the scientific information categories for estuaries (figs. 12 and 17).

E1 – Assessment and Interpretation of Available Hydrodynamic and Water-Quality Information for Norwich Harbor and the Thames River Estuary

Compilation of available data and interpretations from agency and academic studies of Norwich Harbor and the Thames River Estuary is an important resource for future work in the estuary, as is the identification of essential data for understanding the harbor and estuarine system. Questions to address include: What hydrodynamic information is available, and at what locations? What water-quality data sets are available, for what locations, time periods, and frequencies? What data sets were used in past models? What new data sets are being developed? The size and complexity of the system suggest a need for some form of information synthesis as a guide to future investigations. Consultation with estuarine modelers would be an important aspect of assessing existing data and developing data requirements for understanding the system.

E2 – Monitoring to Define Tidal Hydrodynamics in Norwich Harbor

Information on tidal hydrodynamics would be important in understanding water-quality conditions in Norwich Harbor, and to any future modeling efforts. The Acoustic Doppler Current Profiler (ADCP) can be used to acquire the necessary three-dimensional current data. The monitoring effort would be designed to determine the vertical velocity distribution over full tidal cycles and a range of freshwater inflow conditions, including a high streamflow event. The Thames Symposium (Connecticut Department of Environmental Protection, 2002c) identified the development of an estuary model as a high priority for continued TMDL development, and the basic information for such a modeling effort is presently (2004) unavailable.

E3 – Monitoring to Define Water-Quality Variability Over a Range of Climatic and Tidal Conditions in Norwich Harbor

Water-quality conditions in Norwich Harbor are highly variable on a seasonal basis and in the vertical dimension. Detailed information on these variations would be necessary for understanding the ways in which tributary inflows and biological activity within the harbor itself may influence the development of hypoxia. Acquisition of a profiling water-quality monitor is suggested for deployment in Norwich Harbor to collect vertical profiles of water-quality data at small time steps during a range of climatic, hydrologic, and tidal conditions. The profiling monitor includes a probe that can measure site-specific horizontal velocities, and so can be used to relate water-quality conditions to circulation patterns in the harbor. The profiling unit includes the capacity for remote transmission of data. Consequently, the monitor can serve as a window into developing water-quality conditions, and can be the mechanism to trigger synoptic sampling efforts to capture important water-quality events, such as the development of hypoxia. The profiling monitor, although a significant capital expense, is actually an inexpensive approach to acquisition of essential data, when compared with the labor costs of traditional water-quality data-collection efforts.

E4 – Sources of Nutrients and Organic Loads to Norwich Harbor

Multiple sources of nutrients and organic loads to Norwich Harbor have been identified, but a consensus does not currently exist in the scientific community as to which sources are most important in the development of seasonal low dissolved oxygen conditions. A study of sources of nutrients and organic material is suggested to evaluate and quantify external (freshwater) and internal (marine) sources. The investigation would include integration of information from previous studies, as well as field studies in the harbor and estuary. Information from nutrient source and load investigations (F4, 8, 12, 13, 15, 23, 24) in freshwater areas of the Thames River Basin would support this study, as would studies conducted in the harbor (E2, 3). Load estimates for freshwater streams may require additional monitoring downstream from existing long-term gages. Analyses of harbor sediment cores to determine terrestrial or marine origin of organic carbon could include microscopic identification of algae and stable carbon isotope analyses. These analyses may also provide information on changes in the rate of organic carbon accumulation. Information from the water column could include sources, composition, and abundance of algal communities and algal detritus, as well as settling rates. Because of the complex suite of information required, it may be desirable to conduct this study in phases.

E5 – Phytoplankton Community Composition and Dynamics in Freshwater Inflows and Norwich Harbor

As freshwater inflows transport nutrients and organic material into Norwich Harbor, a complex succession of algal communities may take place during the growing season and under different streamflow and tidal conditions. ***Identification of algal community composition under various streamflow and tidal regimes, and integration of this information with hydrodynamic and water-quality information collected in related studies, would provide information for understanding conditions leading to low dissolved oxygen in Norwich Harbor and the Thames River Estuary.***

E6 – Assessment of Sediment Oxygen Demand

Information on sediment distribution, thickness, and composition, as well as information on processes at the sediment-water interface, is important in understanding the role of sediment oxygen demand in creating low dissolved oxygen concentrations in Norwich Harbor. In conjunction with information on terrestrial and marine sources of nutrients and organic material (E4), this study would provide information to identify the key sources of oxygen demand.

E7 – Evaluation of Factors Leading to Low Dissolved Oxygen Conditions in Norwich Harbor

This study would integrate information on tidal hydrodynamics, water quality, nutrient and organic sources, phytoplankton communities, and sediment oxygen demand (E2, 3, 4, 5, 6) to develop an understanding of the development of low dissolved oxygen conditions in Norwich Harbor.

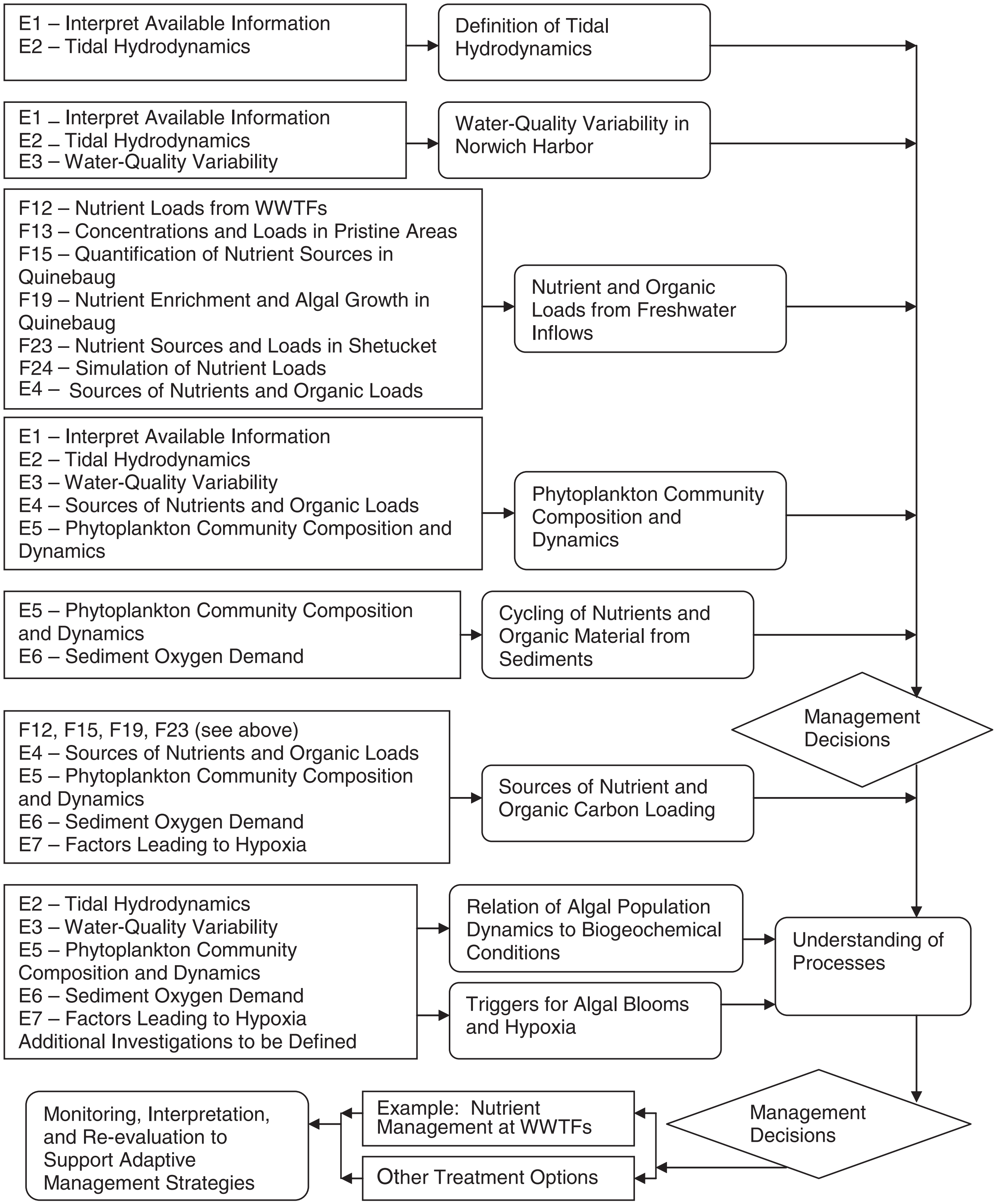

Figure 17. Diagram showing sequence of suggested investigations to support information needs for nutrient TMDL development for Norwich Harbor and its drainage area.

Summary of Key Suggested Investigations

A set of key suggested investigations from this Science Plan is listed in figure 18. These investigations include both freshwater and estuarine studies. These studies are considered key because they provide fundamental information that would support all subsequent higher levels of investigation.

The Thames Science Plan constitutes a major step in the ongoing process of monitoring water quality, interpreting data, and evaluating additional information needs. This process supports the adaptive management approach for the restoration of impaired waters and the protection of unimpaired waters. The Thames Science Plan provides a platform from which water-resource managers can view the larger context of nutrient-related water-quality impairments, focus on the information needed to understand these impairments, and select investigations that would support scientifically defensible management actions.

FRESHWATER INVESTIGATIONS:

- Evaluation of Surface-Water-Quality Sampling Design for the Thames River Basin (F2)
- Annual Nutrient Budget for West Thompson Lake (F7)
- Daily and Seasonal Nutrient Loads at West Thompson Lake (F8)
- Bioavailable Phosphorus in West Thompson Lake Sediment (F9)
- Algal Growth Bioassay for West Thompson Lake (F11)
- Annual and Seasonal Nutrient Loads from Wastewater-Treatment Facilities (F12)
- Quantification of Point and Nonpoint Sources of Nutrients in the Quinebaug River Basin (F15)
- Time of Travel Studies on the Quinebaug River (F16)

ESTUARINE INVESTIGATIONS:

- Assessment and Interpretation of Available Hydrodynamic and Water-Quality Information for Norwich Harbor and the Thames Estuary (E1)
- Monitoring to Define Tidal Hydrodynamics in Norwich Harbor (E2)
- Monitoring to Define Water-Quality Variability Over a Range of Climatic and Tidal Conditions in Norwich Harbor (E3)

Figure 18. Key investigations suggested in the Thames Science Plan.

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